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4 **Dynamics of ripples superimposed on a sand ridge on a tideless shoreface**

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8 **Abstract**

9 The presence of ripples superimposed on an active sand ridge is the most usual situation under low- to  
10 moderate-energy conditions in the wave-dominated, tideless Ebro Delta coast. Four types of small-scale  
11 bedforms were identified, from the critical threshold of sediment motion to wash-out conditions: (i) small  
12 undulations with  $\eta < 0.5$  cm and  $\lambda \sim 8$  cm, formed as a precursor of wave ripples when the Shields  
13 parameter was just below the theoretical critical; (ii) 2D wave ripples with  $\eta = 1.2$  cm and  $\lambda = 7$ -10 cm; (iii)  
14 mixed 2D/3D current-dominated ripples with a maximum of  $\eta \sim 1.5$  cm and  $\lambda = 10$ -15 cm; and (iv) 3D  
15 wave-current ripples with a maximum of  $\eta \sim 2.2$  cm and  $\lambda = 7$ -20 cm. Ripple degradation was observed to  
16 occur when the energy of the hydrodynamic regime increased (wash-out conditions) and under low-  
17 energy hydrodynamic conditions, when ripples progressively decayed mainly as a consequence of  
18 biological activity. The wave ripples were static, while the current-dominated ripples migrated towards  
19 the SE at a rate of  $\sim 10$  cm/h.

20 The potential role of ripple migration as an additional long-term mechanism of sediment transport is  
21 addressed. On the Ebro Delta shoreface, 3D ripple migration follows the direction of sand ridge migration  
22 towards the SE. The respective migration rates and their differences in size support the hypothesis that a  
23 subordinate part of sand ridge migration can result from the contribution of ripple migration under low to  
24 moderate regimes, suggesting that in specific environments the dynamics of small-scale bedforms can  
25 play a subordinate but not negligible role in the evolution of larger bedforms.

26 **Keywords:** ripples, superimposed bedforms, sediment dynamics, bedform migration, inner shelf, Ebro  
27 Delta

## 28 1. Introduction

29 Small-scale bedforms such as ripples are ubiquitous morphological features in sandy coastal and shelf sea  
30 environments. They display typical wavelengths ( $\lambda$ ) of  $\sim 0.05\text{--}0.5$  m and heights ( $\eta$ ) of  $\sim 0.01\text{--}0.1$  m (e.g.  
31 Allen, 1968; Nielsen 1992). Ripples can be generated by wave-, current- or wave- and current-induced  
32 flows (Flemming, 1980) in intermediate flow conditions between the thresholds for grain movement and  
33 sheet flow (Dalrymple and Rhodes, 1995). Morphologically, ripples are generally characterized by a  
34 straight crest alignment (2D ripples) at low speeds or a sinuous, catenary, linguoid, sinuous or lunate crest  
35 alignment (3D ripples) at high speeds (Thorne et al., 2009). Ripple geometries can differ significantly  
36 under wave or current-dominated conditions: wave-generated ripples are typically symmetrical in shape  
37 and have rectilinear crestlines, while in unidirectional flows they are primarily asymmetric and show 3D  
38 morphological features. Wave ripples can also be dynamic bedforms that usually migrate downstream  
39 following the wave skewness (Allen, 1973; Gallagher et al., 1998; Crawford and Hay, 2001).

40 Accurate prediction of ripple geometry is crucial to the modelling of bottom boundary layer dynamics  
41 and sediment transport because the ripple development and variation in bed roughness directly control the  
42 magnitude of bed stress, skin-friction/form-drag partition, near-bed velocity structure, vertical profiles of  
43 suspended sediment concentration and bedload rates (Glenn and Grant, 1987; Grant and Madsen, 1979;  
44 Wiberg and Nelson, 1992; Li et al., 1996; Li and Amos, 1998). Equilibrium ripple predictors based on  
45 extensive laboratory and field datasets have recently been developed for waves (e.g. Soulsby et al., 2012;  
46 Nelson et al., 2013), currents (e.g. Soulsby et al., 2012; Bartholdy et al., 2015) and for combined waves  
47 and currents (e.g. Li and Amos, 1998; Soulsby et al., 2012). Under non-steady forcing conditions, active  
48 ripple patterns and geometrical characteristics continuously adjust or adapt according to changing  
49 hydrodynamic conditions (Traykovski et al., 1999). Equilibrium ripple predictors may not capture this  
50 adaptation process, resulting in limited prediction of ripple dimensions during morphodynamically active

51 periods. To solve this issue, time-evolving (non-steady) ripple predictors have recently been suggested  
52 (Traykovski, 2007; Soulsby et al., 2012).

53 Ripples are frequently superimposed on larger-scale bedforms. The hierarchical nature of bedforms has  
54 long been recognized, with two, three or even four different scales of bedform often occurring in the same  
55 system (e.g. Venditti et al., 2005; Li and King, 2007). Experimental and field data show ripples and small  
56 dunes generally lying on the backs or stoss sides of larger bedforms, many of which grow through  
57 amalgamation of the smaller bedforms, and small embryonic bedforms continually form on the backs of  
58 larger ones (Allen, 1982; Gomez et al., 1989; Venditti et al., 2005; Reesink and Bridge, 2009, 2007;  
59 Naqshband et al., 2014). The size, shape and dynamism of the superimposed forms are a function of the  
60 relative position with respect to the host bedform, and the size, shape and dynamism of the host bedform  
61 are at least partially a function of the superimposed bedform size and dynamics. For example, Cataño-  
62 Lopera and García (2006) observed larger and slightly asymmetric ripples on the crest and smaller and  
63 slightly more symmetrical ripples on the trough, but smaller and very asymmetric ones between the crest  
64 and trough of the primary bedform. When superimposed ripples migrate and reach the crest of a host  
65 bedform, they affect the shape and migration rate of the larger-scale bedform on the lee side and influence  
66 the nature of sediment deposition (Reesink and Bridge, 2007). Under unidirectional flow, the  
67 superimposed bedforms travel faster than the host bedform and overtake it (Reesink and Bridge, 2007),  
68 although the number of superimposed bedforms decreases gradually with the increasing flow velocity  
69 (Reesink and Bridge, 2009). In general, both the ripples and the host bedforms migrate in the same  
70 direction as the wave/current propagation. Typical daily-averaged migration rates in shallow waters are  
71 about 24-80 cm, with specific migration episodes ranging from 0.1 to 2 cm/min, depending mainly on the  
72 cross-shore location and ripple dimensions (Traykovski et al., 1999; Doucette, 2002; Masselink et al.,  
73 2007). Increasing flow speed results in faster migration rates but smaller ripple dimensions (Cataño-  
74 Lopera and García, 2006). Ripple migration rates are of a similar order of magnitude when ripples are  
75 superimposed on larger bedforms as when they are lying on a flatbed, although ripple migration rates  
76 vary depending on the location relative to the host bedform, being slower over troughs and faster over  
77 crests (Cataño-Lopera and García, 2006).

Though the presence of ripples is recurrent in shallow environments and frequently superimposed on larger-scale bedforms, the contribution of ripples to the dynamics of larger bedforms is poorly understood. Therefore, obtaining detailed knowledge of small-scale processes is essential to interpret the larger-scale ones, because the dynamics of the two processes are somehow connected.

This study analyses small-scale bedforms lying superimposed on a sand ridge field on the shoreface of the Ebro Delta. The location of ripples in relation to the larger bedform corresponds to one end of a sand ridge with symmetric geometry lying on the outer part of the prodelta of the former Cape Tortosa river mouth at 13.3 m depth ((a) Ebro Delta location. (b) Subaerial Ebro Delta shaded-relief and bathymetric contours offshore with location of the sand ridge field in grey. Location of tripod, sediment sample and the Buda Island meteorological station). According to Guerrero et al. (2018), NW wind-induced currents are the main cause of sand ridge migration towards the SE, while waves propagated in the opposite direction may be the mechanism for reshaping these forms to more symmetrical morphologies. The development and dynamism of ripples under waves and/or currents and the feasibility of ripple migration as a potential contributor to sand ridge migration are analysed. In addition, the reliability of ripple predictors and sediment transport estimations is discussed.

## **2. Study area**

The Ebro Delta is located off the coast of Spain in the NW of the Mediterranean and it is the third largest delta of the Mediterranean Sea ((a) Ebro Delta location. (b) Subaerial Ebro Delta shaded-relief and bathymetric contours offshore with a), with an emerged area of 325 km<sup>2</sup>. The submerged surface (prodelta) covers an area of ~2300 km<sup>2</sup> of the continental shelf and extends alongshelf up to 110 km southwards from the present river mouth (Díaz et al., 1996). The Ebro Delta is located in a micro-tidal, wave-dominated coast with a maximum astronomical tidal range of 0.25 m. As the tidal currents are negligible, with very weak intensities, and are only detectable in the absence of waves and winds, the Mediterranean Sea is frequently considered a tideless sea (King and Williams, 1949). However, meteorological tides (storm surges) play an important role as they cause increases in sea level of up to ~1 m (Bolaños et al., 2009). This area is characterized by persistent strong, dry and usually cold Mistral

winds that blow from the NW through the Ebro valley (onshore winds) in autumn and winter. The Mistral wind is channelized into a limited band influenced by the orography, forming a seaward wind jet that usually develops in a ~50-km-wide band offshore (Grifoll et al., 2016). The NW winds have a clear seasonal pattern, the most intense and persistent ones occurring in winter and autumn. However, in spring and summer, offshore winds can also reach high intensities (Cerralbo et al., 2015; Grifoll et al., 2016). The NW wind regime results in relatively small waves along the Ebro coast because of the short fetch (<50 km). On the other hand, the most intense swell-dominated storms come from the eastern sectors (E or ENE), where stronger winds coincide with a maximum fetch of approximately 700 km (Bolaños-Sánchez et al., 2007; Sánchez-Arcilla et al., 2008). These storms have an average duration of less than 24 h and typically occur more than 10 times per year, basically concentrated in the periods October-December and March-April (Sánchez-Arcilla et al., 2008). These eastern wave storms have an annual return period significant wave height ( $H_s$ ) of 3.5 m (Bolaños et al., 2009).

Morphodynamics in the Ebro Delta nearshore are dominated by the easterly waves, which generate net alongshore currents directed towards the NW and SW at the north and south of Cape Tortosa, respectively (Jiménez and Sánchez-Arcilla, 1993). Small-scale bedforms (1 cm high and 8-14 cm apart) appear during fair-weather conditions at ~10 m depth on the shoreface of the Ebro Delta, with further vanishing because of seabed bioturbation (Guillén et al., 2008). At the study location, a sand ridge field has been identified lying over the former Cape Tortosa river mouth in the Ebro Delta (Guerrero et al. 2018). The sand ridge field extends between 5 and 15 m depth and has a maximum height and wavelength of approximately 2.5 and 400 m, respectively (Guerrero et al. 2018). The sand ridges are dynamic, with migration rates of ~10 m/y caused by SE-directed wind-induced currents.

### **3. Data acquisition, methodology and materials**

This work is mainly based on field observations. Sediment samples, wind- and wave-field time series, and hydrodynamic and seafloor configuration measurements and observations (the latter obtained from a benthic tripod deployment) were used to analyse the small-scale sedimentary processes on the Ebro Delta shoreface. The data and the methodology used are explained in the following section.

### 3.1. Bottom sediment samples

Sediment samples were collected using a HAPS bottom core on the sand ridge field at the shoreface of the Ebro Delta (see location in (a) Ebro Delta location. (b) Subaerial Ebro Delta shaded-relief and bathymetric contours offshore with location of the sand ridge field in grey. Location of tripod, sediment sample and the Buda Island meteorological station b). The 13-cm-long core was sampled and analysed every centimetre. They were first dried in an oven at 80°C for 24 hours. The sediment fraction finer than 2000  $\mu\text{m}$  was examined using an LA-950V2 laser scattering particle size distribution analyser (HORIBA), while the coarser fraction was sieved using a column with three sieves (6000, 4000 and 2000  $\mu\text{m}$ ). The grain size distribution and the median grain size ( $d_{50}$ ) were estimated.

### 3.2. Winds and waves

Wind field measurements from the Buda Island meteorological station (latitude 40.707° N; longitude 0.834° E) were supplied by the Catalan Meteorological Service (SMC) (see location in (a) Ebro Delta location. (b) Subaerial Ebro Delta shaded-relief and bathymetric contours offshore with location of the sand ridge field in grey. Location of tripod, sediment sample and the Buda Island meteorological station b). The time series data provided wind speed intensities (gust velocity) and directions every 30 minutes. Wind data were obtained from the meteorological station located inland ~5 km to the west of the study area.

Wave field measurements and statistical data were obtained from the offshore buoy of Tarragona provided by the Spanish Ports Authority, with an hourly sampling interval ([www.puertos.es](http://www.puertos.es)). The buoy of Tarragona is located approximately 50 km to the east of the study area at 688 m water depth (latitude 40.680° N; longitude 1.47° E). From October to December 2013, when the strong, NW Mistral winds blew intensively, the Tarragona buoy measured high, mostly because of the long fetch. However, at the tripod location, the NW wind did not have sufficient fetch to develop large waves because it is very close to the coast. In fact, the former Cape Tortosa buoy had been recording wave field data for years and showed a blank region or a lack of waves in a window between 220° and 310° with respect to N (the former Cape Tortosa buoy was situated at 25 m water depth, relatively close to the tripod location).

Therefore, it was highly recommended to integrate wave field and wind conditions in a model able to transform waves, propagating them from the Tarragona buoy to the study area location but also generating and accounting for wind-induced waves from inland winds. To achieve this, the wave field data at the study site were obtained using the SWAN model by simulation of wave generation and propagation along the Ebro Delta shelf from 1 October to 31 December 2013.

The simulations were carried out with the SWAN Cycle III v. 41.20 model (Booij et al., 1999). The simulations were run using the standard values of all parameters recommended in the SWAN user manual. The wind forcing was considered throughout the entire domain to account for wave generation. The wave forcing was defined by the parametric wave spectra: the significant wave height ( $H_s$ ), the peak period ( $T_p$ ), the wave direction and the coefficient of directional spreading, interpreted as the directional standard deviation in degrees. The area of analysis comprised the continental shelf and shoreface of the Ebro Delta. The computational domain ranges from 311778 to 340000 m E and from 4494043 to 4521327 m N in UTM coordinates 31 N zone World Geodetic System (WGS-84). The bathymetry has a 90-m grid resolution and ranges from -100 m at the deepest outer region (E) to -5 m at the Ebro Delta (W). The bathymetric data were extracted from the Catalano-Balearic Sea bathymetric chart (Farrán, 2018). A uniform regular grid made up of more than 43000 computational cells was used (cell size: 140 x 140 m).

SWAN was run in stationary mode ( $\partial N / \partial t = 0$ ) for hourly wind and wave conditions during the study period (October-December 2013), assuming that waves propagate instantaneously throughout the model domain with an immediate response to wind field changes.

### **3.3.Benthic tripod instrumentation**

Instrumented bottom frames have been used since the 1960s to investigate bottom boundary layer processes and sediment dynamics without significant flow interference near the seafloor (Sternberg, 2005). Instruments attached to benthic tripod structures allow scientists to obtain measurements and observations of seabed micro-bathymetry, seafloor images, sediment characteristics, near-bottom hydrodynamics and suspended sediment concentrations.

182 An instrumented benthic tripod was deployed off Cape Tortosa on the Ebro Delta inner shelf over a sand  
183 ridge field at approximately 13 m water depth from 13 October to 31 December 2013 in the framework of  
184 the FORMED project ((a) Ebro Delta location. (b) Subaerial Ebro Delta shaded-relief and bathymetric  
185 contours offshore with location of the sand ridge field in grey. Location of tripod, sediment sample and  
186 the Buda Island meteorological station b).

187 The tripod stood ~2.50 m high and the feet formed an equilateral triangle of 3 m on each side, with  
188 weights at each foot to maintain stability (Image of the tripod structure during the deployment  
189 manoeuvres on the deck of the ship on 13 October 2013. Numbers indicate the position of the instruments  
190 used here: (1) video camera; (2) currentmeter; and (3) altimeter.). The frame was self-contained, fully  
191 submerged, and various batteries, instruments and dataloggers were attached to it. The instruments used  
192 measured current intensities and directions (currentmeter), turbidity (turbidimeters), direct seafloor  
193 images (video camera), and topographic seabed variability (altimeter). The basic instrument  
194 characteristics, location above the bottom (deck of the ship) and sampling strategy are shown in Image of  
195 the tripod structure during the deployment manoeuvres on the deck of the ship on 13 October 2013.  
196 Numbers indicate the position of the instruments used here: (1) video camera; (2) currentmeter; and (3)  
197 altimeter. and Technical characteristics and specifications of the instruments deployed on the Ebro Delta .  
198 The technical characteristics and set-up of the main instruments are described below.

199 An Aanderaa currentmeter (RCM-9) recorded the current intensity and direction at 0.94 m above the  
200 bottom (mab) every 30 minutes using an acoustic Doppler sensor emitting at 2 MHz and a magnetic  
201 compass (Technical characteristics and specifications of the instruments deployed on the Ebro Delta ).  
202 The instrument was also equipped with a turbidity sensor that measured suspended sediment  
203 concentrations at 0.852 mab (Technical characteristics and specifications of the instruments deployed on  
204 the Ebro Delta ).

205 An ALTUS altimeter measured the topographic variability of the seabed, with 2-mm resolution of  
206 changes in elevation of the seabed as the distance from an acoustic transducer located at 0.2 mab every 15  
207 minutes (Technical characteristics and specifications of the instruments deployed on the Ebro Delta ).



ALTUS operation is based on emitting a 2-MHz acoustic wave. The echo signal is filtered, amplified, rectified, and then compared with the programmed threshold to give a detection signal (Jestin et al., 1998). The altimeter time series was post-processed in order to automatically remove the spikes that appeared along the time series. The condition applied consisted in point-by-point comparison with the standard deviation of a 5-point window and substitution of the point with the previous one when it was greater than the deviation.

A GoPro Hero3 Black Edition version 1.1 recorded sequences of 10 seconds (s) every 4 hours (h) at 1.6 mab. The digital video camera provides oblique images at 12-120 frames per second (fps), with video effective pixels of 12 MP. Providing an oblique image, the camera has 1920x1080 resolution and micro HDMI with field-of-view modes. The seabed coverage was approximately 1.9 m<sup>2</sup>.

Table I. Technical characteristics and specifications of the instruments deployed on the Ebro Delta tripod

Instruments	Measurement used	Sampling interval	Location
AANDERAA RCM-9	Horizontal current speed (cm/s) Current direction (Deg. M)	30 min	At 94 cmab
ALTUS 26001	Depth (m) Altitude (mm)	15 min	At 20 cmab
GoPro	Video images	10 s every 4 h	At 163 cmab

### 3.4. Time series data

Specific data quality controls were evaluated for each instrument and sensor following its own protocol and recommendations in order to assess the validity of the measurements. In addition, data were processed to obtain the desired variables as follows:

#### 3.4.1. Ripple observations

Ripple geometry and dimensions are here described as the orientation of the crestlines, sinuosity and the cross-sectional ripple height and wavelength ( $\eta$  and  $\lambda$ , respectively).

The seabed morphology and evolution were analysed using images from the video sequences recorded with the digital video camera. The images provided a useful tool for identifying changes in seabed morphologies and particularly for identifying periods of ripple development. Seabed configurations were

230 schematized and summarized over time. Periods with biological activity were also observed, although  
231 they were not included in the time series. About 18% of the video sequences (those classified as “no  
232 data”) were of poor quality or unclear because of technical failures of the camera, high turbidity levels or  
233 biological activity that covered the visual field of the camera.

234 The altimeter provided direct information about the seabed variability as the distance from the transducer  
235 to the target or seafloor. Ripple heights were estimated from the topographic oscillations of the seabed  
236 level, recorded with the altimeter. The seabed position during each period of ripple formation was  
237 detrended using a polynomial fit to estimate ripple height from fluctuations of the bed elevations around a  
238 horizontal reference level. Then, ripple height was estimated statistically using the root mean square of  
239 the elevation multiplied by a factor equal to  $2\sqrt{2}$ . This is based on assuming a sinusoidal ripple cross  
240 section, since for a sine wave the height is equal to times the elevation of the standard deviation  
241 (Traykovski et al., 1999).

242 The instantaneous images were acquired from the videos and were first geometrically corrected using  
243 ground control points. Then, the ripple wavelengths were measured as the distance between successive  
244 ripple crests, mostly measured at the central areas of the images, where the resolutions as well as the  
245 deformations were optimum. In addition, box plots from the ripples crestlines in the images were used to  
246 distinguish and classify ripple geometries, specifically a box plot of the ripple crest directions and  
247 sinuosity index (length of ripples crest/length of rectilinear ripple crest, where 1 is straight rectilinear  
248 crests).

249 Migration rates were estimated as the time between the passing of two crests recorded with the altimeter.  
250 The ripple crests were first detected (applying a vertical threshold of 0.3 cm) and the distance between the  
251 two crests was assumed to be the time between the passing of a ripple crest. Then, the wavelength  
252 observed in the closest image to the altimeter observations divided by the time of a crest pass was used to  
253 estimate ripple migration.

### 254 3.4.2. Wave field time series

255 The wave field variables used here after the wave propagation explained above were , and wave direction  
256 (). The wind variables used were the maximum half-hourly gust velocity and the respective direction.

### 257 3.4.3. Wave orbital velocity

258 The wave orbital velocity was calculated following small-amplitude linear wave theory for regular waves.  
259 The orbital velocity just above the wave boundary layer over the bed due to monochromatic (single-  
260 frequency) wave height () and period () at water depth () is

261 ..... (eq. 1)

262 where is the hyperbolic sine, is the wavenumber, is the wavelength, and and are the root mean square  
263 wave height and mean wave period, respectively (Soulsby, 2006). The was determined by applying the  
264 Newton-Rapshon iteration method to the dispersion equation following the algorithm of Fenton and  
265 McKee, (1990), which accounts for the effect of the currents and includes the wave-current angle  
266 correction. The wave-current angle is 0° when waves and currents are travelling in the same direction and  
267 180° when they are travelling in opposite directions.

### 268 3.4.4. Bed roughness

269 For bed shear stress and sediment transport purposes, the estimated total roughness length was the sum of  
270 the grain-related or skin friction (), which is responsible for bedload transport (Soulsby 1997), and  
271 sediment transport components ( related to the intensity of transport at very high flow speeds. The form-  
272 drag component, which is associated with turbulence that diffuses the suspended sediment up into the  
273 flow, was not considered. Thus,

274 ..... (eq. 2)

275 where (Soulsby 1997)

276 ..... (eq. 3)

277 ..... for currents (eq. 4)

278 .....for waves (eq. 5)

279 and is the skin-friction shear stress according to Soulsby (1997), ( $\text{kg/m}^3$ ) is the sediment density and  
280 ( $\text{kg/m}^3$ ) is the water density.

#### 281 3.4.5.Bed shear stress

282 The bed shear stress was calculated following the methodology proposed by Soulsby and Clarke (2005)  
283 and modified by Malarkey and Davies (2012) under combined waves and currents for hydrodynamic  
284 rough bed conditions and under the approximation of  $z_0 \ll BL \ll h$ , where BL is the wave boundary  
285 layer thickness and is the depth. The mean bed shear stress due to combined flow () over hydrodynamic  
286 rough beds (sand and gravel beds) is

287 ..... (eq. 6)

288 where is the bed shear stress due to currents alone and is the bed shear stress due to waves alone. This  
289 variable was estimated considering the depth-averaged current speed as the current measured at the  
290 currentmeter depth and considering the bed roughness length of waves and currents estimated as  
291 explained above.

292 Finally, the maximum bed shear stress due to combined flow (Soulsby, 1997) is

293 ..... (eq. 7)

294 where is the angle between the current and the wave travel direction.

#### 295 3.4.6.Shields parameter and its thresholds

296 The Shields parameter ( $\tau^*$ ), also called the Shields criterion or number is a non-dimensional variable used to  
297 identify or determine when seabed states typically reach the initiation of sediment motion in a fluid flow  
298 (van Rijn, 2007a). The Shields parameter also gives an approximation of the boundaries or limits of  
299 seabed morpho-states in relation to the incident hydrodynamic conditions, in our case for a constant  
300 sediment size throughout the study period and evaluated during waves and currents separately (Soulsby et  
301 al., 2012).

302 ..... (eq. 8)

303 The critical Shields parameter for initiation of motion is given as (Soulsby and Whitehouse 1997)

304 ..... (eq. 9)

305 where is the critical threshold for the bed shear stress; is the dimensionless sediment size, with at the  
306 Ebro site; is the relative density; ( $\text{m}^2/\text{s}$ ) is the kinematic viscosity coefficient; ( $\text{m}/\text{s}^2$ ) is the gravity  
307 acceleration; and is the median grain size.

308 The Shields parameter due to waves () and currents is defined as

309 ..... (eq. 10)

310 ..... (eq. 11)

311 During high-energy hydrodynamic conditions, ripples can be washed out. According to Soulsby et al.  
312 (2012), the effect of wash-out at large current speeds can be included using a criterion given in terms of  
313 skin friction Shields parameters as a function of  $D^*$ . Then, the limit of wash-out is

314 when .. (eq. 12)

315 This corresponds to the inception of the sheet flow regime, when most of the sediment transport occurs in  
316 a thin layer close to the bed (Camenen and Larson, 2006). Camenen (2009) reviewed some of the  
317 expressions proposed and developed an evaluation of sheet flow estimations. Because the expressions are  
318 based on empirical equations, they resulted in great variability. The skin-friction sheet flow threshold as  
319 a function of  $D^*$  proposed by Soulsby et al. (2012) is

320 when .. (eq. 13)

### 321 3.4.7. Ripple prediction

322 Ripple predictors to estimate the bedform characteristics are mostly exclusively focussed on ripple  
323 geometry parameters: height and wavelength. These predictors are usually defined for current-generated,

wave-generated or combined flow ripples. (Wiberg and Harris, 1994; Soulsby and Whitehouse, 2005; van Rijn, 2007b; Camenen, 2009; Maier and Hay, 2009; Soulsby et al., 2012; Nelson and Voulgaris, 2014).

For instance, Nelson and Voulgaris (2015) developed a 2D model based on Soulsby and Whitehouse (2005) ripple prediction and introducing the Traykovski (2007) spectral model able to predict ripple orientation, shape and slope that improved ripple predictions for waves-dominated and waves influenced by currents conditions. The use of different approaches trying to improve ripple prediction is out of the aims of this study, but it is a topic that deserves further research. Given the available field data and the clear hydrodynamic conditions, the methodology of the theory of equilibrium ripple dimensions of Soulsby et al. (2012) is used here because of its simplicity and because it is based on the comparison of the Shields parameter thresholds obtained with the hydrodynamic measurements. The Shields thresholds are compared with Shields due to waves () leading to wave-generated ripples and with Shields due to currents () leading to current-generated ripples. When waves dominate (), the estimated ripple dimensions grow when the energy increases and decay when the energy decreases, because they are a direct function of the wave orbital velocity. When currents dominate (), current ripples can develop when with constant and maximum bedform dimensions. Under increasing energy, a linear reduction in ripple height is defined between and , and it is assumed that the wavelength is unaffected by wash-out, being equivalent to the maximum value. When currents dominate over waves, ripple dimensions decrease () until they completely wash out, imposing flatbed () (Soulsby et al., 2012). Finally, for waves and currents acting together, this ripple prediction model assumes that only the dominant ripple train of the two is present at any time (Li and Amos, 1998).

#### 3.4.8. Sediment transport rate

The sediment transport rate was estimated following the van Rijn (2007a, 2007b) methodology because of its simplicity for obtaining estimations of the bedload and suspended load sediment transport in coastal flows. The method only requires the basic hydrodynamic parameters (depth, current velocity, wave height, wave period, etc.) and the basic sediment characteristics ( $d_{50}$ ) (van Rijn, 2007a). In addition, the formula is universal in the sense that it can be applied to the full range of sediment sizes (8-2000  $\mu\text{m}$ ) and the full hydrodynamic regimes (including coastal flows).

#### 351 3.4.9. Suspended sediment concentration

352 The turbidity time series were used to obtain the suspended sediment concentration at ~1 mab. The data  
353 were processed to correct inconsistent values in three steps: (i) checking values larger than the average of  
354 the two preceding measurements plus 100; (ii) checking measurements larger than the previous and  
355 following values plus 20; and (iii) removing values that meet the two conditions and replacing them with  
356 their average.

## 357 4. **Results**

### 358 4.1. **Waves and near-bottom current time series**



359 The at the tripod location ranged from 0.1 m to maximum values of ~3 m, with several periods of >1 m  
360 (Time series from October to December 2013 of (a) seabed configurations distinguishing the  
361 morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross),  
362 ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated  
363 significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots)  
364 at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability)  
365 measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013  
366 shown in Detail from 23 October to 16 November of the same time series variables as those described in  
367 the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing  
368 the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples  
369 (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b)  
370 propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and  
371 direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic  
372 variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16  
373 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as  
374 those described in the caption of Time series from October to December 2013 of (a) seabed  
375 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
376 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
377 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
378 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
379 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
380 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
381 series variables as those described in the caption of Time series from October to December 2013 of (a)  
382 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
383 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
384 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
385 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
386 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

377 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 378 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 379 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 380 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 381 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 382 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 383 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 384 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 385 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 386 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 387 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 388 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 389 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 390 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 391 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 392 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 393 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 394 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 395 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 396 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 397 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 398 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple  
 399 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
 400 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 401 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 402 The coloured shaded areas indicate the ripple morphologies observed.. b). The highest waves (>2 m)  
 403 occurred mostly during November and early December and represented conditions of moderate wave  
 404 storms with peak wave periods () of 8 and 12 s. The storms were clearly eastern storms (locally called

405 “Llevantades”), with only one exception on 24 December, when waves came from the S (Time series  
406 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
407 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
408 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
409 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
410 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
411 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
412 October to 16 November of the same time series variables as those described in the caption of Time series  
413 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
414 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
415 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
416 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
417 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
418 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
419 October to 16 November of the same time series variables as those described in the caption of Time series  
420 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
421 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
422 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
423 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
424 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
425 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
426 October to 16 November of the same time series variables as those described in the caption of Time series  
427 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
428 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
429 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
430 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
431 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
432 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23

407 October to 16 November of the same time series variables as those described in the caption of Time series  
 408 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 409 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 410 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 411 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 412 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 413 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 414 October to 16 November of the same time series variables as those described in the caption of Time series  
 415 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 416 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 417 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 418 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 419 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 420 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 421 October to 16 November of the same time series variables as those described in the caption of Time series  
 422 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 423 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 424 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 425 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 426 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 427 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The  
 428 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 429 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 430 The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas  
 431 indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies  
 432 observed.. b). Following the waves, the near-bottom orbital velocity () displayed several peaks >0.4 m/s,  
 433 mostly between November and early December, and a maximum peak of 0.8 m/s on 16 November (Time  
 434 series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or

408 states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
409 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
410 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
411 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
412 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
413 October to 16 November of the same time series variables as those described in the caption of Time series  
414 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
415 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
416 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
417 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
418 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
419 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
420 October to 16 November of the same time series variables as those described in the caption of Time series  
421 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
422 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
423 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
424 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
425 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
426 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
427 October to 16 November of the same time series variables as those described in the caption of Time series  
428 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
429 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
430 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
431 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
432 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
433 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
434 October to 16 November of the same time series variables as those described in the caption of Time series  
435 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states

409 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 410 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 411 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 412 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 413 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 414 October to 16 November of the same time series variables as those described in the caption of Time series  
 415 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 416 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 417 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 418 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 419 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 420 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 421 October to 16 November of the same time series variables as those described in the caption of Time series  
 422 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 423 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 424 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 425 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 426 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 427 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The  
 428 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 429 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 430 The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas  
 431 indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies  
 432 observed.. d).

410 The current speed measurements at ~1 mab showed periods of intense currents between November and  
411 December, similarly to the wave heights (Time series from October to December 2013 of (a) seabed  
412 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
413 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
414 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
415 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
416 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
417 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
418 series variables as those described in the caption of Time series from October to December 2013 of (a)  
419 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
420 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
421 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
422 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
423 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
424 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
425 series variables as those described in the caption of Time series from October to December 2013 of (a)  
426 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
427 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
428 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
429 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
430 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
431 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
432 series variables as those described in the caption of Time series from October to December 2013 of (a)  
433 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
434 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
435 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
436 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
437 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

438 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 439 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 440 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 441 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 442 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 443 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 444 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 445 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 446 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 447 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 448 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 449 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 450 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 451 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 452 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 453 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 454 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 455 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 456 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 457 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 458 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 459 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple  
 460 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
 461 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 462 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 463 The coloured shaded areas indicate the ripple morphologies observed.. c). The maximum speed recorded  
 464 was ~0.6 m/s on 16 November and 27 December. When current speeds increased over 0.2 m/s, they were  
 465 always channelized towards the SSE.



## 441    **4.2.Seabed morphological changes and ripple observations**

442    The surficial bottom sediment at the tripod location on the 13<sup>th</sup> October 2013 was fine sand with a median  
443    sediment grain size ( $d_{50}$ ) of 210  $\mu\text{m}$ . The sediment was composed with two grain size populations: the  
444    91% of well-sorted fine sand with a mode around 230  $\mu\text{m}$  and the 9% of mud mostly silt (Bottom  
445    sediment grain size distribution of the surficial sample (0-1 cm) at the tripod location on the 13th of  
446    October of 2013.).

447 The altimeter was able to measure the topographic variability of the seabed from the beginning of the  
 448 deployment until 16 November, when the most energetic storm measured occurred (Time series from  
 449 October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 450 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 451 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 452 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 453 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 454 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 455 October to 16 November of the same time series variables as those described in the caption of Time series  
 456 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 457 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 458 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 459 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 460 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 461 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 462 October to 16 November of the same time series variables as those described in the caption of Time series  
 463 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 464 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 465 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 466 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 467 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 468 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 469 October to 16 November of the same time series variables as those described in the caption of Time series  
 470 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 471 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 472 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 473 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 474 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.

475 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 476 October to 16 November of the same time series variables as those described in the caption of Time series  
 477 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 478 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 479 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 480 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 481 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 482 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 483 October to 16 November of the same time series variables as those described in the caption of Time series  
 484 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 485 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 486 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 487 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 488 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 489 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 490 October to 16 November of the same time series variables as those described in the caption of Time series  
 491 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 492 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 493 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 494 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 495 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 496 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The  
 497 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 498 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 499 The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas  
 500 indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies  
 501 observed.. e). During this period a settle of ~10 cm was first recorded on 17 October, probably as a  
 502 consequence of the structure stabilizing (Time series from October to December 2013 of (a) seabed

476 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
 477 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 478 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 479 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 480 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 481 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 482 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 483 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 484 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 485 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 486 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 487 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 488 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 489 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 490 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 491 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 492 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 493 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 494 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 495 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 496 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 497 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 498 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 499 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 500 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 501 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 502 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 503 series variables as those described in the caption of Time series from October to December 2013 of (a)

504 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
505 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
506 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
507 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
508 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
509 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
510 series variables as those described in the caption of Time series from October to December 2013 of (a)  
511 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
512 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
513 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
514 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
515 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
516 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
517 series variables as those described in the caption of Time series from October to December 2013 of (a)  
518 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
519 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
520 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
521 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
522 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
523 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple  
524 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
525 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
526 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
527 The coloured shaded areas indicate the ripple morphologies observed.. e). The seabed position

508 measurements alternated between steady and oscillating topographic periods (Time series from October  
 509 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 510 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 511 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 512 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 513 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 514 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 515 November of the same time series variables as those described in the caption of Time series from October  
 516 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 517 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 518 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 519 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 520 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 521 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 522 November of the same time series variables as those described in the caption of Time series from October  
 523 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 524 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 525 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 526 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 527 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 528 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 529 November of the same time series variables as those described in the caption of Time series from October  
 530 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 531 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 532 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 533 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 534 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 535 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16

509 November of the same time series variables as those described in the caption of Time series from October  
 510 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 511 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 512 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 513 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at  $\sim 1$  mab; (d)  
 514 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 515 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 516 November of the same time series variables as those described in the caption of Time series from October  
 517 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 518 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 519 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 520 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at  $\sim 1$  mab; (d)  
 521 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 522 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 523 November of the same time series variables as those described in the caption of Time series from October  
 524 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 525 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 526 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 527 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at  $\sim 1$  mab; (d)  
 528 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 529 indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas  
 530 indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies  
 531 observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded  
 532 areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple  
 533 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. e).  
 534 Seabed oscillations displayed fluctuations of the order of 20 cm, and smaller oscillations of the order of a

511 few centimetres (Detail from 23 October to 16 November of the same time series variables as those  
 512 described in the caption of Time series from October to December 2013 of (a) seabed configurations  
 513 distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-  
 514 current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data  
 515 (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s  
 516 (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed  
 517 topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October  
 518 to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables  
 519 as those described in the caption of Time series from October to December 2013 of (a) seabed  
 520 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
 521 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 522 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 523 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 524 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 525 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 526 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 527 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 528 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 529 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 530 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 531 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 532 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 533 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 534 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 535 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 536 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 537 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 538 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from



539 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 540 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 541 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 542 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 543 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 544 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 545 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 546 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 547 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 548 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 549 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 550 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 551 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 552 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 553 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 554 series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple  
 555 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
 556 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 557 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 558 The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas  
 559 indicate the ripple morphologies observed. e), the latter related to ripple development periods.

540 Six periods of ripple formation were identified from the images of the video camera during the first  
 541 month of deployment (Time series from October to December 2013 of (a) seabed configurations  
 542 distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-  
 543 current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data

544 (star); (b) propagated significant wave height in m (line) and direction (dots); (c) a, Detail from 23  
 545 October to 16 November of the same time series variables as those described in the caption of Time series  
 546 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 547 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 548 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 549 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 550 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 551 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 552 October to 16 November of the same time series variables as those described in the caption of Time series  
 553 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 554 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 555 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 556 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 557 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 558 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 559 October to 16 November of the same time series variables as those described in the caption of Time series  
 560 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 561 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 562 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 563 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 564 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 565 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 566 October to 16 November of the same time series variables as those described in the caption of Time series  
 567 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 568 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 569 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 570 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 571 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.

572 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
573 October to 16 November of the same time series variables as those described in the caption of Time series  
574 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
575 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
576 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
577 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
578 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.

579 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
580 October to 16 November of the same time series variables as those described in the caption of Time series  
581 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
582 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
583 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
584 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
585 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.

586 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
587 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The  
588 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
589 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
590 The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas  
591 indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies  
592 observed... The coloured shaded areas indicate the ripple morphologies observed. a). In general, ripples  
593 developed during low- to moderate-energy hydrodynamic conditions. They were typically generated by  
594 the action of waves and/or currents and their size was well correlated with the flow energy, exhibiting  
595 greater dimensions under high-energy conditions and smaller dimensions under low-energy conditions.  
596 At the end of each ripple development period, these small bedforms degraded progressively when the

577 energy decreased or increased above the wash-out threshold (Time series from October to December  
 578 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle),  
 579 wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle),  
 580 undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction  
 581 (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital  
 582 velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 583 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 584 November of the same time series variables as those described in the caption of Time series from October  
 585 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 586 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 587 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 588 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 589 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 590 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 591 November of the same time series variables as those described in the caption of Time series from October  
 592 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 593 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 594 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 595 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 596 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 597 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 598 November of the same time series variables as those described in the caption of Time series from October  
 599 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 600 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 601 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 602 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 603 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 604 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16

605 November of the same time series variables as those described in the caption of Time series from October  
606 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
607 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
608 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
609 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
610 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
611 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
612 November of the same time series variables as those described in the caption of Time series from October  
613 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
614 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
615 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
616 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
617 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
618 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
619 November of the same time series variables as those described in the caption of Time series from October  
620 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
621 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
622 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
623 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
624 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
625 indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas  
626 indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies  
627 observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded  
628 areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple

morphologies observed... The coloured shaded areas indicate the ripple morphologies observed.. a, Detail  
 from 23 October to 16 November of the same time series variables as those described in the caption of  
 Time series from October to December 2013 of (a) seabed configurations distinguishing the  
 morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross),  
 ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated  
 significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots)  
 at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability)  
 measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013  
 shown in Detail from 23 October to 16 November of the same time series variables as those described in  
 the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing  
 the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples  
 (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b)  
 propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and  
 direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic  
 variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16  
 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as  
 those described in the caption of Time series from October to December 2013 of (a) seabed  
 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and

634 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
635 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
636 series variables as those described in the caption of Time series from October to December 2013 of (a)  
637 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
638 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
639 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
640 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
641 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
642 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
643 series variables as those described in the caption of Time series from October to December 2013 of (a)  
644 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
645 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
646 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
647 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
648 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
649 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
650 series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple  
651 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
652 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
653 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
654 The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas  
655 indicate the ripple morphologies observed. a). 2D ripples formed during low-energy hydrodynamic  
656 conditions and were associated with waves (~1 m), while 3D ripples formed under slightly higher (but

636 moderate) energy conditions and were associated with waves and currents (Detail from 23 October to 16  
 637 November of the same time series variables as those described in the caption of Time series from October  
 638 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 639 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 640 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 641 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 642 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 643 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 644 November of the same time series variables as those described in the caption of Time series from October  
 645 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 646 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 647 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 648 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 649 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 650 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 651 November of the same time series variables as those described in the caption of Time series from October  
 652 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 653 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 654 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 655 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 656 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 657 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 658 November of the same time series variables as those described in the caption of Time series from October  
 659 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 660 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 661 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 662 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 663 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area



664 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
665 November of the same time series variables as those described in the caption of Time series from October  
666 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
667 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
668 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
669 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
670 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
671 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
672 November of the same time series variables as those described in the caption of Time series from October  
673 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
674 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
675 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
676 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
677 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
678 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
679 November of the same time series variables as those described in the caption of Fig. 3. The coloured  
680 shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple  
681 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
682 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
683 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
684 The coloured shaded areas indicate the ripple morphologies observed.).

### 665 4.3.Ripple classification

666 Plan view seabed morphologies were distinguished and classified as follows: flat bottom; small  
667 undulations; 2D ripples (ripples with rectilinear crests); 3D ripples (ripples with sinuous crests); ripple  
668 decay or degradation; and no data, when images were not available or quality was too low to identify any

669 morphology on the seabed (Time series from October to December 2013 of (a) seabed configurations  
 670 distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-  
 671 current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data  
 672 (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s  
 673 (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed  
 674 topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October  
 675 to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables  
 676 as those described in the caption of Time series from October to December 2013 of (a) seabed  
 677 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
 678 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 679 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 680 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 681 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 682 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 683 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 684 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 685 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 686 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 687 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 688 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 689 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 690 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 691 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 692 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 693 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 694 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 695 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 696 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time

697 series variables as those described in the caption of Time series from October to December 2013 of (a)  
698 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
699 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
700 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
701 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
702 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
703 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
704 series variables as those described in the caption of Time series from October to December 2013 of (a)  
705 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
706 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
707 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
708 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
709 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
710 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
711 series variables as those described in the caption of Time series from October to December 2013 of (a)  
712 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
713 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
714 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
715 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
716 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
717 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple  
718 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
719 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
720 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
721 The coloured shaded areas indicate the ripple morphologies observed.. a, Detail from 23 October to 16  
722 November of the same time series variables as those described in the caption of Time series from October  
723 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
724 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse

698 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 699 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 700 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 701 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 702 November of the same time series variables as those described in the caption of Time series from October  
 703 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 704 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 705 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 706 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 707 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 708 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 709 November of the same time series variables as those described in the caption of Time series from October  
 710 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 711 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 712 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 713 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 714 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 715 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 716 November of the same time series variables as those described in the caption of Time series from October  
 717 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 718 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 719 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 720 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 721 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 722 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 723 November of the same time series variables as those described in the caption of Time series from October  
 724 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 725 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse

726 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
727 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
728 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
729 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
730 November of the same time series variables as those described in the caption of Time series from October  
731 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
732 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
733 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
734 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
735 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
736 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
737 November of the same time series variables as those described in the caption of Fig. 3. The coloured  
738 shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple  
739 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
740 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
741 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
742 The coloured shaded areas indicate the ripple morphologies observed. a). A complete description was  
743 obtained using the images recorded with the video camera, the time series of the propagated and  
744 direction, current velocity measured at ~1 mab, the seabed topographic variations measured with the  
745 altimeter, the measurements of the suspended sediment concentration at ~1 mab and the estimations of  
746 near-bottom stresses at the boundary layer.

#### 731 4.3.1. Undulations

732 During low-energy hydrodynamic conditions, small undulations were observed lying on the seabed  
733 (Example of the undulations observed in the instantaneous images from the video record on 1 November  
734 at 19 h.). The small bedforms were not classified as ripple bedforms because they were not sufficiently  
735 well developed, showing crests without a clear continuity in length and small dimensions ( < 0.5 cm and  
736 ~8 cm) (Example of the undulations observed in the instantaneous images from the video record on 1  
737 November at 19 h.). These undulations formed during periods of waves of  $\lambda = 0.5\text{-}1\text{ m}$  and low current

738 speed ( $< 0.1$  m/s) (Detail from 23 October to 16 November of the same time series variables as those  
739 described in the caption of Time series from October to December 2013 of (a) seabed configurations  
740 distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-  
741 current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data  
742 (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s  
743 (line) and direction (dots) at the tripod location at  $\sim 1$  mab; (d) orbital velocity (); and (e) a (seabed  
744 topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October  
745 to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables  
746 as those described in the caption of Time series from October to December 2013 of (a) seabed  
747 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
748 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
749 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
750 current speed in m/s (line) and direction (dots) at the tripod location at  $\sim 1$  mab; (d) orbital velocity (); and  
751 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
752 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
753 series variables as those described in the caption of Time series from October to December 2013 of (a)  
754 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
755 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
756 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
757 current speed in m/s (line) and direction (dots) at the tripod location at  $\sim 1$  mab; (d) orbital velocity (); and  
758 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
759 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
760 series variables as those described in the caption of Time series from October to December 2013 of (a)  
761 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
762 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
763 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
764 current speed in m/s (line) and direction (dots) at the tripod location at  $\sim 1$  mab; (d) orbital velocity (); and  
765 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from





771 periods of wave-dominated hydrodynamic conditions (wave ripples) (Detail from 23 October to 16  
772 November of the same time series variables as those described in the caption of Time series from October  
773 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
774 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
775 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
776 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
777 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
778 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
779 November of the same time series variables as those described in the caption of Time series from October  
780 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
781 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
782 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
783 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
784 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
785 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
786 November of the same time series variables as those described in the caption of Time series from October  
787 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
788 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
789 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
790 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
791 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
792 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
793 November of the same time series variables as those described in the caption of Time series from October  
794 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
795 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
796 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
797 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
798 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area

799 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 800 November of the same time series variables as those described in the caption of Time series from October  
 801 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 802 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 803 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 804 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 805 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 806 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 807 November of the same time series variables as those described in the caption of Time series from October  
 808 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 809 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 810 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 811 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 812 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 813 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 814 November of the same time series variables as those described in the caption of Fig. 3. The coloured  
 815 shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple  
 816 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
 817 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 818 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 819 The coloured shaded areas indicate the ripple morphologies observed. and Example of 2D ripple  
 820 formation observed in the instantaneous images (a) on 27 October at 23 h; (b) benthic community  
 821 contribution to ripple degradation on 28 October at 19 h). Two periods of 2D ripple development were  
 822 identified.

803 2D ripples were first observed on 27 October at 19 h, and at 23 h they were even better developed during  
 804 a small (< 1 m) eastern storm (Example of 2D ripple formation observed in the instantaneous images (a)  
 805 on 27 October at 23 h a). The ripples displayed rectilinear N-S-oriented crests, with mean 1.2 cm and 7-

806 10 cm (0.15) (Example of 2D ripple formation observed in the instantaneous images (a) on 27 October at  
807 23 h a). The analysis of the temporal seabed topographic variation and the ripple crest geometries and  
808 positions revealed that they were static, with neither migration nor dynamism. Previous images (26  
809 October) showed the presence of undulations at the beginning of the eastern wave event (  $\sim 1$  m),  
810 suggesting that the pre-existing undulations acted as precursors of ripple formation (Detail from 23  
811 October to 16 November of the same time series variables as those described in the caption of Time series  
812 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
813 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
814 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
815 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
816 location at  $\sim 1$  mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
817 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
818 October to 16 November of the same time series variables as those described in the caption of Time series  
819 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
820 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
821 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
822 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
823 location at  $\sim 1$  mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
824 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
825 October to 16 November of the same time series variables as those described in the caption of Time series  
826 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
827 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
828 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
829 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
830 location at  $\sim 1$  mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
831 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
832 October to 16 November of the same time series variables as those described in the caption of Time series  
833 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states

834 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 835 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 836 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 837 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 838 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 839 October to 16 November of the same time series variables as those described in the caption of Time series  
 840 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 841 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 842 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 843 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 844 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 845 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 846 October to 16 November of the same time series variables as those described in the caption of Time series  
 847 from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states  
 848 observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or  
 849 degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave  
 850 height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod  
 851 location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab.  
 852 The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23  
 853 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The  
 854 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 855 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 856 The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas  
 857 indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies  
 858 observed... The coloured shaded areas indicate the ripple morphologies observed. a). Finally, the ripples  
 859 degraded progressively mainly due to the biological activity of the benthic community (Example of 2D  
 860 ripple formation observed in the instantaneous images (a) on 27 October at 23 h; (b) benthic community  
 861 contribution to ripple degradation on 28 October at 19 h b).

838 A second period of N-S-oriented, straight-crest ripple morphologies with mean 0.5 cm (maximum  
839 heights of 1 cm) and 6-8 cm (0.07) formed between 19 and 23 h on 3 November, when eastern waves  
840 increased to ~1 m (Example of 2D ripple formation observed in the instantaneous images (a) on 27  
841 October at 23 h; (b) benthic community contribution to ripple degradation on 28 October at 19 h; and (c)  
842 on 4 November at 3 h. c). The previous seabed state was “flatbed” with some roughness resulting from  
843 the biological activity, but no undulations were previously observed. The 2D ripples also remained static  
844 on the seabed, with neither dynamism nor migration.

#### 845 4.3.3. Mixed 2D/3D ripples

846 Mixed 2D/3D ripples were characterized as dynamic bedforms that changed their arrangement from  
847 sinuous to rectilinear crests with larger dimensions than those of the 2D ripples described above ((a)  
848 Sinuosity and (b) ripple crest direction box plots of the four periods when different ripples morphologies  
849 were observed., Example of ripple formation under current-dominated conditions observed in the  
850 instantaneous images on (a) 4 November at 19 h; (b) 4 November at 23 h; (c) 5 November at 3 h; (d) 5  
851 November at 19 h; (e) 6 November at 3 h; and (f) 6 November at 19 h.). 2D ripples presented low  
852 sinuosity while 3D ripples morphologies resulted in sinuosity indexes further from one and crestlines  
853 directions with a wide variability ((a) Sinuosity and (b) ripple crest direction box plots of the four periods  
854 when different ripples morphologies were observed.). These ripples occurred during current-dominated  
855 hydrodynamic conditions (current ripples) and were observed during three different periods in November

856 (Detail from 23 October to 16 November of the same time series variables as those described in the  
 857 caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the  
 858 morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross),  
 859 ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated  
 860 significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots)  
 861 at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability)  
 862 measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013  
 863 shown in Detail from 23 October to 16 November of the same time series variables as those described in  
 864 the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing  
 865 the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples  
 866 (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b)  
 867 propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and  
 868 direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic  
 869 variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16  
 870 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as  
 871 those described in the caption of Time series from October to December 2013 of (a) seabed  
 872 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
 873 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 874 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 875 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 876 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 877 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 878 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 879 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 880 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 881 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 882 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 883 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... For example, a rippled bed with sinuous crests and small dimensions developed on 4 November at 19 h under high-speed currents ( $>0.3$  m/s), just after the

886 previous wave ripple formation described above (Detail from 23 October to 16 November of the same  
 887 time series variables as those described in the caption of Time series from October to December 2013 of  
 888 (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 889 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 890 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 891 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 892 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 893 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 894 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 895 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 896 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 897 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 898 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 899 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 900 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 901 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 902 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 903 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 904 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 905 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 906 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 907 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 908 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 909 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 910 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 911 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 912 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 913 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from



914 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 915 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 916 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 917 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 918 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 919 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 920 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 921 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 922 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 923 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 924 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 925 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 926 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 927 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 928 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 929 series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple  
 930 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
 931 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 932 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 933 The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas  
 934 indicate the ripple morphologies observed. a; Example of ripple formation under current-dominated  
 935 conditions observed in the instantaneous images on (a) 4 November at 19 h; (b) 4 November at 23 h; (c) 5  
 936 November at 3 h a). The size of ripples increased/decreased following the current speeds (Example of  
 937 ripple formation under current-dominated conditions observed in the instantaneous images on (a) 4  
 938 November at 19 h; (b) 4 November at 23 h; (c) 5 November at 3 h; (d) 5 November at 19 h a, b, c).  
 939 Moderate currents (0.2-0.3 m/s) flowing towards the S led to modification of the ripple morphologies  
 940 from 3D to 2D (crests oriented W-E), completely removing the residual ripple morphologies from the  
 941 previous wave ripple period (Example of ripple formation under current-dominated conditions observed

922 in the instantaneous images on (a) 4 November at 19 h; (b) 4 November at 23 h; (c) 5 November at 3 h;  
923 (d) 5 November at 19 h; (e) 6 November at 3 h; and (f) 6 November at 19 h. d, e). Finally, the ripples  
924 degraded, displaying rounded crests and poorly-defined shapes under lower current speed (Example of  
925 ripple formation under current-dominated conditions observed in the instantaneous images on (a) 4  
926 November at 19 h; (b) 4 November at 23 h; (c) 5 November at 3 h; (d) 5 November at 19 h; (e) 6  
927 November at 3 h; and (f) 6 November at 19 h. f). The mean ripple height was estimated at around 0.8 cm  
928 (maximum >1.5 cm) and the wavelength ( $\lambda$ ) around 10-15 cm ( $\lambda/\text{cm} = 0.05-0.15$ ) for the whole period of  
929 appearance. The ripples migrated towards the SSE at rates of 6-10 cm/h.

#### 929 4.3.4. 3D ripples

930 3D ripples displayed sinuous crests morphologies resulting in sinuosity indexes further from one and  
931 ripples directions diverged ((a) Sinuosity and (b) ripple crest direction box plots of the four periods when  
932 different ripples morphologies were observed.). 3D ripples had larger dimensions than the 2D ripples and

933 were formed under wave-current hydrodynamic conditions (Detail from 23 October to 16 November of  
934 the same time series variables as those described in the caption of Time series from October to December  
935 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle),  
936 wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle),  
937 undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction  
938 (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital  
939 velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
940 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
941 November of the same time series variables as those described in the caption of Time series from October  
942 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
943 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
944 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
945 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
946 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
947 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
948 November of the same time series variables as those described in the caption of Time series from October  
949 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
950 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
951 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
952 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
953 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
954 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
955 November of the same time series variables as those described in the caption of Time series from October  
956 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
957 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
958 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
959 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
960 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area

961 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 962 November of the same time series variables as those described in the caption of Time series from October  
 963 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 964 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 965 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 966 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 967 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 968 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 969 November of the same time series variables as those described in the caption of Time series from October  
 970 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 971 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 972 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 973 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 974 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 975 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 976 November of the same time series variables as those described in the caption of Fig. 3. The coloured  
 977 shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple  
 978 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
 979 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 980 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 981 The coloured shaded areas indicate the ripple morphologies observed.). They migrated towards the S  
 982 accordingly with the current flow.

963 3D ripple morphologies were observed for the first time on 29 October at 7 h (Example of 3D ripple  
 964 formation under wave-current-dominated conditions observed in the instantaneous images on (a) 29  
 965 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h  
 966 a) and lasted until 31 October, when the ripples started to decline (Example of 3D ripple formation under  
 967 wave-current-dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29

968 October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h; and (f) 31 October at  
969 7 h. f). Previous to the development of 3D ripples, the seabed configuration displayed slight roughness  
970 elements: small undulations corresponding to the residual morphologies from the former 2D ripples  
971 (Detail from 23 October to 16 November of the same time series variables as those described in the  
972 caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the  
973 morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross),  
974 ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated  
975 significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots)  
976 at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability)  
977 measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013  
978 shown in Detail from 23 October to 16 November of the same time series variables as those described in  
979 the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing  
980 the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples  
981 (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b)  
982 propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and  
983 direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic  
984 variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16  
985 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as  
986 those described in the caption of Time series from October to December 2013 of (a) seabed  
987 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
988 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
989 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
990 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
991 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
992 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
993 series variables as those described in the caption of Time series from October to December 2013 of (a)  
994 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
995 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations

995 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 996 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 997 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 998 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 999 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1000 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1001 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1002 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1003 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1004 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1005 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1006 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1007 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1008 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1009 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1010 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1011 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1012 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1013 series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple  
 1014 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
 1015 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 1016 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 1017 The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas  
 1018 indicate the ripple morphologies observed. a). The 3D ripples progressively readapted their morphologies  
 1019 and sizes by growing and displaying better-defined crests as a result of the increasing currents and wave  
 1020 heights (e.g. Example of 3D ripple formation under wave-current-dominated conditions observed in the  
 1021 instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30  
 1022 October at 3 h; (e) 31 October at 3 h; and (f) 31 October at 7 h. c-e). However, they also degraded slightly

during the second and highest current speed peak ( $v \sim 0.5$  m/s) and wave heights ( $= 1.2$  m) of the event on 30 October (Example of 3D ripple formation under wave-current-dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h; and (f) 31 October at 7 h. d). Finally, the ripples degraded progressively at the end of this wave-current event (Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at  $\sim 1$  mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at  $\sim 1$  mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at  $\sim 1$  mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave

1028 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1029 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1030 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1031 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1032 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1033 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1034 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1035 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1036 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1037 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1038 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1039 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1040 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1041 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1042 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1043 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1044 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1045 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1046 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1047 series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple  
 1048 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
 1049 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 1050 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 1051 The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas  
 1052 indicate the ripple morphologies observed. a, Example of 3D ripple formation under wave-current-  
 1053 dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15  
 1054 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h; and (f) 31 October at 7 h. f). Ripple



mean height was 1.9 cm, with maximum ripple height values of ~2.2 cm and 7-20 cm (0.10-0.25). These ripples were highly dynamic, with migration rates of 5-13 cm/h towards the SSE. Video-records during these events revealed the presence of fishes swimming against the current flow (perpendicular to the ripple crest arrangement) (e.g. Example of 3D ripple formation under wave-current-dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h b) and the oscillatory movement (parallel to ripple crests) of sand and shells, presumably induced by the eastern waves (e.g. in the video of the instantaneous image Example of 3D ripple formation under wave-current-dominated conditions observed in the instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30 October at 3 h; (e) 31 October at 3 h d).

#### 4.4. Seabed mobility

The hydrodynamic forcing conditions acting on the seabed during the study period were characterized by estimating the Shields parameter generated by waves and currents (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) b). The maximum Shields parameter due to waves () was reached on 16 November, and after this event a few peaks of  $> 0.2$  occurred. Current Shields parameter peaks ranged between 0.1 and 0.2, coinciding with the highest peaks in the near-bottom current speeds (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) b). The estimated Shields parameter thresholds of motion, wash-out and sheet flow conditions were 0.05, 0.19 and 0.26, respectively (Shields parameter thresholds for critical, wash-out and sheet flow conditions obtained with different ). The comparison between the Shields parameter due to waves and these thresholds suggested that ~17.2% of the time, 1% of the time and 0.4% of the time. The remaining 81.4% of time the hydrodynamics induced by waves was below the threshold of sediment motion. The Shields parameter due to currents () exceeded the theoretical critical threshold of grain motion ~12.9% of

the time, but it was always below the threshold of wash-out conditions (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) b). In summary, considering both wave and current Shields parameters, critical conditions for grain movement were exceeded during 24% of the time and wash-out and sheet flow were only reached during 1% and 0.4% of the time, respectively, under high-energy waves. The remaining 74.6% of the time conditions were below the critical threshold of motion.

Table II. Shields parameter thresholds for critical, wash-out and sheet flow conditions obtained with different approaches.

Author(s)	hydrodynamic conditions				
	defined method				
Nielsen (1981)	-	-	1	-	oscillatory flow
Li and Amos (1999)	-	-	0.2	-	steady and oscillatory combined
Kleinhans (2005)	-	-	[0-0.56]	-	steady and oscillatory combined
Soulsby and Whitehouse (2005)	-	-		~2000	oscillatory flow
Soulsby et al. (2012)	0.05	0.19	0.26	-	steady and oscillatory combined



1068 Most of the estimated near-bottom sediment transport occurred in short pulses during severe storms  
 1069 (Time series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at  
 1070 ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (),  
 1071 wash-out () and sheet flow (); (c) total sediment transport rate (), suspended sediment transport rate () and  
 1072 bedload sediment transport rate (); (d) ripple wavelengths in cm from observations (red dots) and  
 1073 obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple wavelength in cm  
 1074 from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black dots). Grey-  
 1075 shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater  
 1076 than the critical threshold, and coloured shaded areas indicate the periods of ripple development detailed  
 1077 in Detail from 23 October to 16 November of the same time series variables as those described in the  
 1078 caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the  
 1079 morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross),  
 1080 ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated  
 1081 significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots)  
 1082 at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability)  
 1083 measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013  
 1084 shown in Detail from 23 October to 16 November of the same time series variables as those described in  
 1085 the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing  
 1086 the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples  
 1087 (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b)  
 1088 propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and  
 1089 direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic  
 1090 variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16  
 1091 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as  
 1092 those described in the caption of Time series from October to December 2013 of (a) seabed  
 1093 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
 1094 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1095 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)

1096 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1097 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1098 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1099 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1100 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1101 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1102 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1103 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1104 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1105 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1106 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1107 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1108 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1109 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1110 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1111 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1112 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1113 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1114 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1115 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1116 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1117 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1118 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1119 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple  
1120 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
1121 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
1122 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
1123 The coloured shaded areas indicate the ripple morphologies observed.. c). Peaks of sediment transport

1097 ranging from 100 to 400 g/s/m occurred from mid-November to early December, with the maximum on  
 1098 16 November (Time series from October to December of (a) turbidity in normalized turbidity units  
 1099 (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of  
 1100 sediment motion (), wash-out () and sheet flow (); (c) total sediment transport rate (), suspended sediment  
 1101 transport rate () and bedload sediment transport rate (); (d) ripple wavelengths in cm from observations  
 1102 (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple  
 1103 wavelength in cm from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black  
 1104 dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents)  
 1105 were greater than the critical threshold, and coloured shaded areas indicate the periods of ripple  
 1106 development detailed in Detail from 23 October to 16 November of the same time series variables as  
 1107 those described in the caption of Time series from October to December 2013 of (a) seabed  
 1108 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
 1109 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1110 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1111 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1112 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1113 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1114 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1115 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1116 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1117 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1118 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1119 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1120 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1121 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1122 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1123 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1124 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)

1125 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1126 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1127 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1128 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1129 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1130 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1131 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1132 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1133 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1134 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1135 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1136 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1137 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1138 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1139 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1140 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1141 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1142 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1143 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1144 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1145 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1146 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1147 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1148 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple  
1149 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
1150 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
1151 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
1152 The coloured shaded areas indicate the ripple morphologies observed.. c). Several smaller peaks of ~20

1126 g/s/m were also estimated under moderate conditions (e.g. on 26 November and on 21 December) (Time  
 1127 series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1  
 1128 mab; (b) wave and current Shields parameter () and the thresholds of initiation of sediment motion (),  
 1129 wash-out () and sheet flow (); (c) total sediment transport rate (), suspended sediment transport rate () and  
 1130 bedload sediment transport rate (); (d) ripple wavelengths in cm from observations (red dots) and  
 1131 obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple wavelength in cm  
 1132 from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black dots). Grey-  
 1133 shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater  
 1134 than the critical threshold, and coloured shaded areas indicate the periods of ripple development detailed  
 1135 in Detail from 23 October to 16 November of the same time series variables as those described in the  
 1136 caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the  
 1137 morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross),  
 1138 ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated  
 1139 significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots)  
 1140 at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability)  
 1141 measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013  
 1142 shown in Detail from 23 October to 16 November of the same time series variables as those described in  
 1143 the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing  
 1144 the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples  
 1145 (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b)  
 1146 propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and  
 1147 direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic  
 1148 variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16  
 1149 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as  
 1150 those described in the caption of Time series from October to December 2013 of (a) seabed  
 1151 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
 1152 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1153 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)



1154 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1155 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1156 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1157 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1158 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1159 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1160 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1161 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1162 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1163 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1164 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1165 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1166 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1167 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1168 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1169 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1170 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1171 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1172 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1173 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1174 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1175 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1176 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1177 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple  
1178 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
1179 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
1180 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
1181 The coloured shaded areas indicate the ripple morphologies observed.. c). In general, the sediment

1155 transport rate was high during events when waves dominated, although most of them were wave-current  
 1156 events (Time series from October to December of (a) turbidity in normalized turbidity units (NTU)  
 1157 measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds of initiation of  
 1158 sediment motion (), wash-out () and sheet flow (); (c) total sediment transport rate (), suspended sediment  
 1159 transport rate () and bedload sediment transport rate (); (d) ripple wavelengths in cm from observations  
 1160 (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple  
 1161 wavelength in cm from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black  
 1162 dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents)  
 1163 were greater than the critical threshold, and coloured shaded areas indicate the periods of ripple  
 1164 development detailed in Detail from 23 October to 16 November of the same time series variables as  
 1165 those described in the caption of Time series from October to December 2013 of (a) seabed  
 1166 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
 1167 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1168 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1169 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1170 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1171 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1172 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1173 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1174 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1175 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1176 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1177 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1178 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1179 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1180 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1181 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1182 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)

1183 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1184 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1185 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1186 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1187 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1188 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1189 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1190 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1191 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1192 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1193 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1194 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1195 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1196 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1197 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1198 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1199 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1200 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1201 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1202 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1203 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1204 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1205 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1206 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple  
1207 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
1208 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
1209 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
1210 The coloured shaded areas indicate the ripple morphologies observed.. c). Estimations suggested that the

1184 sediment transport was widely dominated by suspended load rather than bedload (92% and 8%,  
 1185 respectively), in agreement with observations of suspended sediment concentration (inferred from  
 1186 turbidity measurements), which displayed a strong relation to high-energy wave-current conditions (Time  
 1187 series from October to December of (a) turbidity in normalized turbidity units (NTU) measured at ~1  
 1188 mab; (b) wave and current Shields parameter ( $\tau_{*}$ ) and the thresholds of initiation of sediment motion ( $\tau_{*c}$ ),  
 1189 wash-out ( $\tau_{*w}$ ) and sheet flow ( $\tau_{*s}$ ); (c) total sediment transport rate ( $Q_{tot}$ ), suspended sediment transport rate ( $Q_{susp}$ ) and  
 1190 bedload sediment transport rate ( $Q_{bed}$ ); (d) ripple wavelengths in cm from observations (red dots) and  
 1191 obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple wavelength in cm  
 1192 from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black dots). Grey-  
 1193 shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater  
 1194 than the critical threshold, and coloured shaded areas indicate the periods of ripple development detailed  
 1195 in Detail from 23 October to 16 November of the same time series variables as those described in the  
 1196 caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the  
 1197 morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross),  
 1198 ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated  
 1199 significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots)  
 1200 at the tripod location at ~1 mab; (d) orbital velocity ( $U_{orb}$ ); and (e) a (seabed topographic variability)  
 1201 measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013  
 1202 shown in Detail from 23 October to 16 November of the same time series variables as those described in  
 1203 the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing  
 1204 the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples  
 1205 (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b)  
 1206 propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and  
 1207 direction (dots) at the tripod location at ~1 mab; (d) orbital velocity ( $U_{orb}$ ); and (e) a (seabed topographic  
 1208 variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16  
 1209 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as  
 1210 those described in the caption of Time series from October to December 2013 of (a) seabed  
 1211 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples

1186 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1187 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1188 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1189 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1190 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1191 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1192 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1193 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1194 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1195 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1196 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1197 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1198 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1199 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1200 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1201 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1202 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1203 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1204 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1205 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1206 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1207 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1208 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1209 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1210 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1211 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple  
1212 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
1213 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the

1214 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
1215 The coloured shaded areas indicate the ripple morphologies observed.. a). In general, the measured  
1216 turbidity peaks were well correlated with periods when the Shields parameter exceeded the critical

1241 threshold (grey-shaded areas in Time series from October to December of (a) turbidity in normalized  
1242 turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the thresholds  
1243 of initiation of sediment motion (), wash-out () and sheet flow (); (c) total sediment transport rate (),  
1244 suspended sediment transport rate () and bedload sediment transport rate (); (d) ripple wavelengths in cm  
1245 from observations (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black dots);  
1246 and (e) ripple wavelength in cm from observations and obtained with the ripple predictor of Soulsby et al.  
1247 (2012) (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves  
1248 and/or currents) were greater than the critical threshold, and coloured shaded areas indicate the periods of  
1249 ripple development detailed in Detail from 23 October to 16 November of the same time series variables  
1250 as those described in the caption of Time series from October to December 2013 of (a) seabed  
1251 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
1252 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1253 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1254 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1255 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1256 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1257 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1258 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1259 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1260 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1261 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1262 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1263 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1264 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1265 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1266 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1267 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1268 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and

1269 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1270 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1271 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1272 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1273 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1274 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1275 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1276 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1277 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1278 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1279 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1280 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1281 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1282 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1283 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1284 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1285 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1286 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1287 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1288 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1289 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1290 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1291 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple  
 1292 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
 1293 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
 1294 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
 1295 The coloured shaded areas indicate the ripple morphologies observed.. a). During periods of 3D ripple  
 1296 development, 83% of the sediment transport was attributed to suspended load and the remaining 17% to



1271 bedload.

## 1272 5. Discussion

### 1273 5.1. Ripple occurrence and prediction

1274 Video observations of ripples on the Ebro Delta are biased, being limited to low and moderate  
1275 hydrodynamic conditions because during storm events the high suspended sediment concentration  
1276 prevents seabed video observations. From low to moderate energy, the observations suggest a transition  
1277 from undulations on the seabed to 2D wave ripples (~1 m), current-dominated 2D/3D ripples, and finally  
1278 the largest wave-current 3D ripples. Ripple decay also occurred when the hydrodynamic regime increased  
1279 the energy (wash-out), or because of biological activity (mostly of the benthic community) that  
1280 progressively degraded the bedforms (e.g. Example of 2D ripple formation observed in the instantaneous  
1281 images (a) on 27 October at 23 h; (b) benthic community contribution to ripple degradation on 28  
1282 October at 19 h; and (c) on 4 November at 3 h. b), as observed and suggested previously by Guillén et al.  
1283 (2008) and Soulsby et al. (2012).

1284 Most ripple formation observations at the study site coincide with periods when the Shields parameter  
1285 exceeded the threshold condition for initiation of sediment motion (0.05) (Detail from 23 October to 16  
1286 November of time series of (a) wave and current Shields parameter ( $\tau_{*w}$ ) and the thresholds of initiation of  
1287 sediment motion ( $\tau_{*c}$ ), wash-out ( $\tau_{*w}$ ) and sheet flow ( $\tau_{*s}$ ); (b) total sediment transport rate ( $q_t$ ), suspended  
1288 sediment transport rate ( $q_s$ ) and bedload sediment transport rate ( $q_b$ ); (c) ripple wavelengths in cm from  
1289 observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d)  
1290 ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black  
1291 dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents)  
1292 were greater than the critical Shields parameter ( $\tau_{*c}$ ). However, undulations can be formed on the seabed  
1293 below the critical Shields limit under small waves (0.5-1 m) and weak currents ( $v < 0.1$  m/s) (Detail from  
1294 23 October to 16 November of time series of (a) wave and current Shields parameter ( $\tau_{*w}$ ) and the thresholds  
1295 of initiation of sediment motion ( $\tau_{*c}$ ), wash-out ( $\tau_{*w}$ ) and sheet flow ( $\tau_{*s}$ ); (b) total sediment transport rate ( $q_t$ ),  
1296 suspended sediment transport rate ( $q_s$ ) and bedload sediment transport rate ( $q_b$ ); (c) ripple wavelengths in

1297 cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots);  
 1298 and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor  
 1299 (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or  
 1300 currents) were greater than the critical Shields parameter., Time series from October to December 2013 of  
 1301 (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1302 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1303 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1304 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1305 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1306 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1307 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1308 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1309 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1310 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1311 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1312 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1313 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1314 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1315 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1316 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1317 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1318 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1319 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1320 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1321 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1322 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1323 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1324 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)

1322 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1323 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1324 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1325 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1326 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1327 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1328 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1329 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1330 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1331 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1332 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1333 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1334 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1335 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1336 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1337 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1338 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1339 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1340 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1341 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1342 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1343 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1344 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1345 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas indicate the ripple  
1346 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
1347 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
1348 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...

1323 The coloured shaded areas indicate the ripple morphologies observed.. and Detail from 23 October to 16  
 1324 November of the same time series variables as those described in the caption of Time series from October  
 1325 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 1326 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 1327 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 1328 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 1329 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 1330 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 1331 November of the same time series variables as those described in the caption of Time series from October  
 1332 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 1333 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 1334 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 1335 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 1336 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 1337 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 1338 November of the same time series variables as those described in the caption of Time series from October  
 1339 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 1340 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 1341 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 1342 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 1343 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 1344 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 1345 November of the same time series variables as those described in the caption of Time series from October  
 1346 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 1347 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 1348 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 1349 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 1350 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area

1351 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
1352 November of the same time series variables as those described in the caption of Time series from October  
1353 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
1354 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
1355 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
1356 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
1357 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
1358 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
1359 November of the same time series variables as those described in the caption of Time series from October  
1360 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
1361 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
1362 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
1363 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
1364 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
1365 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
1366 November of the same time series variables as those described in the caption of Fig. 3. The coloured  
1367 shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple  
1368 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed... The  
1369 coloured shaded areas indicate the ripple morphologies observed... The coloured shaded areas indicate the  
1370 ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies observed...  
1371 The coloured shaded areas indicate the ripple morphologies observed.). These undulations ( $< 5$  mm) are  
1372 precursors of 2D ripples if the waves remain constant or increase slightly, as observed on 26 October  
1373 (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter () and  
1374 the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment  
1375 transport rate (qt), suspended sediment transport rate (qs) and bedload sediment transport rate (qb); (c)  
1376 ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple  
1377 predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al  
1378 (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields

1359 parameters (waves and/or currents) were greater than the critical Shields parameter.). The transition from  
 1360 a plane bed to well-developed ripples through the formation of smaller bedforms ( $< 3$  mm) as precursors  
 1361 was previously observed with high-speed flows ( $> 0.65$  m/s) (Reesink and Bridge, 2007), although this  
 1362 transition seems to occur during low-energy wave conditions in the Ebro. The shortage of available  
 1363 records during higher-energy periods prevents a detailed comparison of theoretical wash-out and sheet  
 1364 flow thresholds with observations. The 3D ripple decay occurred during a wave-current peak (on 30  
 1365 October and suggests the initiation of ripple wash-out with 0.1, when the measured current speed was  
 1366 above 0.55 m/s (Detail from 23 October to 16 November of time series of (a) wave and current Shields  
 1367 parameter () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow ()); (b) total  
 1368 sediment transport rate ( $q_t$ ), suspended sediment transport rate ( $q_s$ ) and bedload sediment transport rate  
 1369 ( $q_b$ ); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012)  
 1370 ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby  
 1371 et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields  
 1372 parameters (waves and/or currents) were greater than the critical Shields parameter.).

1373 The application of the ripple predictor approach based on the critical Shields parameter (Soulsby et al.,  
 1374 2012) roughly fits with the appearance of ripples (Detail from 23 October to 16 November of time series  
 1375 of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion (), wash-  
 1376 out () and sheet flow ()); (b) total sediment transport rate ( $q_t$ ), suspended sediment transport rate ( $q_s$ ) and  
 1377 bedload sediment transport rate ( $q_b$ ); (c) ripple wavelengths in cm from observations (red dots) and  
 1378 obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from  
 1379 observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas  
 1380 indicate the interval times when the Shields parameters (waves and/or currents) were greater than the  
 1381 critical Shields parameter. a). However, undulations and 2D ripples were also observed below or near the  
 1382 theoretical threshold of initiation of sediment motion (Detail from 23 October to 16 November of time  
 1383 series of (a) wave and current Shields parameter () and the thresholds of initiation of sediment motion ()),  
 1384 wash-out () and sheet flow ()); (b) total sediment transport rate ( $q_t$ ), suspended sediment transport rate ( $q_s$ )  
 1385 and bedload sediment transport rate ( $q_b$ ); (c) ripple wavelengths in cm from observations (red dots) and

1386 obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from  
1387 observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas  
1388 indicate the interval times when the Shields parameters (waves and/or currents) were greater than the  
1389 critical Shields parameter.). The ripple predictor slightly underestimated ripple wavelength (Detail from  
1390 23 October to 16 November of time series of (a) wave and current Shields parameter ( $\tau_{*c}$ ) and the thresholds  
1391 of initiation of sediment motion ( $\tau_{*m}$ ), wash-out ( $\tau_{*w}$ ) and sheet flow ( $\tau_{*s}$ ); (b) total sediment transport rate ( $q_t$ ),  
1392 suspended sediment transport rate ( $q_s$ ) and bedload sediment transport rate ( $q_b$ ); (c) ripple wavelengths in  
1393 cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots);  
1394 and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor  
1395 (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or  
1396 currents) were greater than the critical Shields parameter. c), while it underestimated ripple heights under  
1397 wave-dominated conditions and overestimated them under current-dominated conditions (Detail from 23  
1398 October to 16 November of time series of (a) wave and current Shields parameter ( $\tau_{*c}$ ) and the thresholds of  
1399 initiation of sediment motion ( $\tau_{*m}$ ), wash-out ( $\tau_{*w}$ ) and sheet flow ( $\tau_{*s}$ ); (b) total sediment transport rate ( $q_t$ ),  
1400 suspended sediment transport rate ( $q_s$ ) and bedload sediment transport rate ( $q_b$ ); (c) ripple wavelengths in  
1401 cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots);  
1402 and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor  
1403 (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or  
1404 currents) were greater than the critical Shields parameter. d). However, in general the dimensions  
1405 differences were low in the order of a few centimetres for the wavelength and millimetres for ripple  
1406 height. In addition, the ripple predictor failed under mixed wave-current conditions, probably because of  
1407 the assumption that only one of the two mechanisms (waves or currents) is the dominant one and because  
1408 the method is not well defined for 3D ripples. The ripple predictor model improves considerably when the  
1409 values of Shields parameters of ripples appearance, degradation and wash-out extracted from the  
1410 observations are applied instead of the theoretical thresholds of critical, wash-out and sheet flow,  
1411 respectively. . Thus, though the approach of Soulsby et al. (2012) has been shown to yield one of the best  
1412 predictions for ripple characteristics, it still suffers inaccuracies because of the estimation of the Shields  
1413 parameter, it fails to account properly for the inception of sheet flow, and it largely overestimates the

1411 results when ripples are washed out (Camenen, 2009). Ripples are usually assumed to be non-equilibrium  
1412 state features in a field that show rapid (at times even ephemeral) variability in their formation and  
1413 dynamism. Therefore, ripple prediction is still working in progress and should be improved by adjusting  
1414 field observations and modelling because prediction of ripple appearance and dimensions is highly  
1415 valuable in the estimation of bed roughness, a decisive parameter in boundary layer processes.

## 1416 **5.2.Ripples and sand ridge dynamics**

1417 Ripples at the study site lay superimposed on the extreme and deepest part of the SE face of a symmetric  
1418 sand ridge. Only mixed 2D/3D and 3D ripples were dynamic, with changing morphologies and  
1419 arrangements adapting to the hydrodynamics and migrating towards the SE accordingly with the current  
1420 flow direction. However, 2D wave ripples remained fixed and stable. Though wave asymmetry can be an  
1421 additional mechanism of ripple migration (Traykovski et al., 1999), wave ripples were static in the Ebro  
1422 area, probably because near-bottom wave velocities at the study site were symmetric or very slightly  
1423 asymmetric during low- and moderate-energy periods of wave ripple observations.

1424 Both ripples and sand ridges migrate towards the SSE as a consequence of wind-induced currents and it is  
1425 feasible that ripples make some contribution to sand ridge dynamics. Generally, large-scale bedforms  
1426 tend to move more slowly than small-scale features (Venditti et al., 2005). The migrating superimposed  
1427 bedforms overtake the larger ones and avalanche on the lee side of them, contributing to the migration of  
1428 the host bedforms (Reesink and Bridge, 2009). The scale of sediment transport involved in the migration  
1429 of superimposed and host bedforms differs, although it can be nearly identical if size and migration rates  
1430 of the two are proportional, i.e. ripples move 10 times faster and are 0.1 times the size of the host bedform  
1431 (Venditti et al., 2005).

1432 At the study site, the highest sediment transport occurred when the Shields parameter exceeded the  
1433 theoretical wash-out threshold, which was in the absence of ripples. In the presence of 2D/3D ripples  
1434 (between the critical and wash-out theoretical thresholds), the sediment transport was one order of



1435 magnitude lower than the highest peaks (Time series from October to December of (a) turbidity in  
1436 normalized turbidity units (NTU) measured at ~1 mab; (b) wave and current Shields parameter () and the  
1437 thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (c) total sediment transport  
1438 rate (), suspended sediment transport rate () and bedload sediment transport rate (); (d) ripple wavelengths  
1439 in cm from observations (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black  
1440 dots); and (e) ripple wavelength in cm from observations and obtained with the ripple predictor of  
1441 Soulsby et al. (2012) (black dots). Grey-shaded areas indicate the interval times when the Shields  
1442 parameters (waves and/or currents) were greater than the critical threshold, and coloured shaded areas  
1443 indicate the periods of ripple development detailed in Detail from 23 October to 16 November of the  
1444 same time series variables as those described in the caption of Time series from October to December  
1445 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle),  
1446 wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle),  
1447 undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction  
1448 (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital  
1449 velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
1450 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
1451 November of the same time series variables as those described in the caption of Time series from October  
1452 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
1453 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
1454 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
1455 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
1456 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
1457 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
1458 November of the same time series variables as those described in the caption of Time series from October  
1459 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
1460 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
1461 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
1462 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)

1463 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 1464 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 1465 November of the same time series variables as those described in the caption of Time series from October  
 1466 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 1467 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 1468 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 1469 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 1470 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 1471 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 1472 November of the same time series variables as those described in the caption of Time series from October  
 1473 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 1474 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 1475 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 1476 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 1477 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 1478 indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16  
 1479 November of the same time series variables as those described in the caption of Time series from October  
 1480 to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat  
 1481 bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse  
 1482 triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and  
 1483 direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d)  
 1484 orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area  
 1485 indicates the detail from 23 October to 16 November 2013 shown in Fig. 5.. The coloured shaded areas  
 1486 indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple morphologies  
 1487 observed... The coloured shaded areas indicate the ripple morphologies observed... The coloured shaded  
 1488 areas indicate the ripple morphologies observed... The coloured shaded areas indicate the ripple  
 1489 morphologies observed... The coloured shaded areas indicate the ripple morphologies observed..), while  
 1490 for Shields values slightly above or below the critical value of sediment motion, when undulations and

the 2D stationary wave ripples developed, the estimated sediment transport was almost null (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter ( $\tau_{*c}$ ) and the thresholds of initiation of sediment motion ( $\tau_{*b}$ ), wash-out ( $\tau_{*w}$ ) and sheet flow ( $\tau_{*s}$ ); (b) total sediment transport rate ( $q_t$ ), suspended sediment transport rate ( $q_s$ ) and bedload sediment transport rate ( $q_b$ ); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter.). In presence of 3D ripples (29 to 31 October) a peak of total sediment transport was estimated, with 83% due to suspended load and the remaining 17% due to bedload (Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter ( $\tau_{*c}$ ) and the thresholds of initiation of sediment motion ( $\tau_{*b}$ ), wash-out ( $\tau_{*w}$ ) and sheet flow ( $\tau_{*s}$ ); (b) total sediment transport rate ( $q_t$ ), suspended sediment transport rate ( $q_s$ ) and bedload sediment transport rate ( $q_b$ ); (c) ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents) were greater than the critical Shields parameter. b). Therefore, the bedload transport could have partially occurred in the form of 3D ripple migration.

Ripple migration was observed during current conditions and combined wave and current conditions when flows were lower than 0.55 m/s and . The instantaneous ripple migration rates estimated from observations were  $\sim 10$  cm/h. The extrapolation of ripple migration rates to periods when provides a rough estimation of the mean ripple migration of 1.3 cm/h during the study period, which should be lower over the year because of the low-energy summer period. Moreover, the annual sand ridge migration rate was  $\sim 10$  m/y (Guerrero et al., 2018), representing a mean rate of 0.11 cm/h. A rough comparison between ripple/sand ridge mean size (0.015 /1.5 m) and migration rates (1.3 /0.11 cm/h) suggests, according to the relationships established by Venditti et al. (2005), that the sediment transport associated with ripple migration could be one order of magnitude lower than the total transport involved in sand ridge migration. This would be a subordinate but non-negligible amount of the bedload sediment transport

associated with bedform migration. While most of the sediment transport and sand ridge migration would occur under sheet flow conditions when ripples were washed out during high-energy episodes, sand ridge migration would also occur during low- to moderate-energy hydrodynamic conditions.

In a more general perspective, the contribution of small bedforms to the growth of larger bedforms and, after formation, the presence of ephemeral small bedforms migrating on the backs of the larger ones have been described (Allen, 1982; Gomez et al., 1989; Venditti et al., 2005; Reesink and Bridge, 2009, 2007). The contribution of small bedforms as ripples during low- to moderate-energy hydrodynamics can help to understand the formation, dynamics and maintenance of large bedforms with no need to resort exclusively to high-energy conditions. For instance, it was hypothesized that low- to moderate-energy processes could explain the maintenance of the morphology of large-scale sand ridges on the continental shelf (Simarro et al., 2015). On the shoreface of the Ebro Delta, the sand ridge could also be dynamic during moderate current episodes because of ripple migration. If this is the case, our vision of large bedforms that remain static during most of the time and are only active during high-energy or extreme conditions should be changed.

## **6. Conclusions**

Seabed morphological observations showed that the presence of ripples is the most usual seabed configuration on the Ebro Delta shoreface during low and moderate hydrodynamic conditions. Four types of small-scale bedforms were identified, from values just below the critical threshold of sediment motion to wash-out conditions: (i) small undulations with 0.5 cm and 8 cm, formed as precursors of wave ripples when the Shields parameter was just below the critical level; (ii) 2D wave ripples with 1.2 cm and 7-10 cm; (iii) mixed 2D/3D current-dominated ripples with 0.8 cm (max. ~1.5 cm) and 10-15 cm; and (iv) 3D wave-current ripples with 1.9 cm (max. ~2.2 cm) and 7-20 cm. Ripple degradation occurred when the hydrodynamic regime increased the energy (wash-out conditions), or under low-energy hydrodynamic conditions, when ripples progressively decayed mainly as a consequence of biological activity by the benthic community, which flattened the relict ripples.

The ripple predictor method roughly fits with the appearance of ripples but fails to predict ripple dimensions, especially during wave-current conditions. The development of small seabed undulations below the theoretical threshold of grain movement is a major concern in ripple and sediment transport prediction, suggesting that the estimated thresholds are progressive ranges rather than abrupt changes.

Most sediment transport occurred during severe storms and under sheet flow conditions when ripples were washed out. In presence of ripples, only during the development of 3D wave-current ripples was significant sediment transport estimated. Observations of the suspended sediment and ripple development also demonstrated that under low- to moderate-energy conditions 2D ripples (wave ripples) formed and remained static features (probably because of the wave orbital velocity symmetry). However, when the energy induced by eastern waves increased, the ripples were washed out and large amounts of fine sand and mud were resuspended and available to be transported towards the NW-W.

Mean ripple migration rates were  $\sim 10$  cm/h during only current and wave-current events. Migration of 3D ripples was dominated by the wind-induced current towards the SSE, which is the same direction as that of sand ridge migration on the Ebro shoreface. Accordingly, it was hypothesized that part of the sand ridge migration could be associated with ripple migration. Rough estimations suggest that the input of ripples to the migration of sand ridges could be no more than one order of magnitude lower than the total transport involved in sand ridge migration. However, this subordinate amount of sediment transport is representative because it suggests that large-scale bedforms could be dynamic during low- to moderate-energy processes and not only during high-energy or extreme conditions.

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## 1546 8. References

1547 Allen, J.R.L. 1968. Current Ripples: Their Relation to Patterns of Water and Sediment Motion. North  
1548 Holland, Amsterdam. 433pp

1549 Allen, J.R.L., 1973. A classification of climbing-ripple cross-lamination. J. Geol. Soc. London. 129, 537–  
1550 541. doi:10.1144/gsjgs.129.5.0537

1551 Allen, J.R.L., 1982. Simple models for the shape and symmetry of tidal sand waves: (1) statically stable  
1552 equilibrium forms. Mar. Geol. 48, 31–49

1553 Bartholdy, J., Ernsten, V.B., Flemming, B.W., Winter, C., Bartholomä, A., Kroon, A., 2015. On the  
1554 formation of current ripples. Sci. Rep. 5: 11390, 1–9. doi:10.1038/srep11390

1555 Bolaños-Sanchez, R., Sanchez-Arcilla, A., Cateura, J., 2007. Evaluation of two atmospheric models for  
1556 wind-wave modelling in the NW Mediterranean. J. Mar. Syst. 65, 336–353.  
1557 doi:10.1016/j.jmarsys.2005.09.014

1558 Bolaños, R., Jorda, G., Cateura, J., Lopez, J., Puigdefabregas, J., Gomez, J., Espino, M., 2009. The  
1559 XIOM: 20 years of a regional coastal observatory in the Spanish Catalan coast. J. Mar. Syst. 77,  
1560 237–260. doi:10.1016/j.jmarsys.2007.12.018

1561 Booij, N., Ris, R.C., Holthuijsen, L.H., 1999. A third-generation wave model for coastal regions: 1.  
1562 Model description and validation. J. Geophys. Res. 104, 7649–7666. doi:10.1029/98JC02622

1563 Camenen, B., 2009. Estimation of the wave-related ripple characteristics and induced bed shear stress.  
1564 Estuar. Coast. Shelf Sci. 84, 553–564. doi:10.1016/j.ecss.2009.07.022

1565 Camenen, B., Larson, M., 2006. Phase-lag effects in sheet flow transport. Coast. Eng. 53, 531–542.

1566 doi:10.1016/j.coastaleng.2005.12.003

1567 Cataño-Lopera, Y.A., García, M.H., 2006. Geometry and migration characteristics of bedforms under  
1568 waves and currents. Part 2: Ripples superimposed on sandwaves. *Coast. Eng.* 53, 781–792.

1569 doi:10.1016/j.coastaleng.2006.03.008

1570 Cerralbo, P., Grifoll, M., Moré, J., Bravo, M., Afif, A.S., Espino, M., 2015. Wind variability in a coastal  
1571 area (Alfacs Bay, Ebro River delta). In *Advances in Science and Research*. pp. 11–21.

1572 doi:10.5194/asr-12-11-2015

1573 Crawford, A.M., Hay, A.E., 2001. Linear transition ripple migration and wave orbital velocity skewness :  
1574 Observations. *J. Geophys. Res.* 106, 14113–14128

1575 Dalrymple, R.W., Rhodes, R.N., 1995. Estuarine dunes and bars. In: *Geomorphology and Sedimentology*  
1576 of Estuaries. *Developments in Sedimentology*. pp. 359–422

1577 Díaz, J.I., Palanques, A., Nelson, C.H., Guillén, J., 1996. Morpho-structure and sedimentology of the  
1578 Holocene Ebro prodelta mud belt (northwestern Mediterranean Sea). *Cont. Shelf Res.* 16, 435–456.

1579 doi:10.1016/0278-4343(95)00019-4

1580 Doucette, Jeffrey S., 2002. Bedform Migration and Sediment Dynamics in the Nearshore of a Low-  
1581 Energy Sandy Beach in Southwestern Australia. *Journal of Coastal Reseach*. vol 18, nº 3, pp. 576-  
1582 591

1583 Farrán, M. Catalano-Balearic Sea (NW Mediterranean): Bathymetric Chart and Toponyms. Available  
1584 online: [http://gma.icm.csic.es/sites/default/files/geowebs/MCB/CBSbats\\_cat.htm](http://gma.icm.csic.es/sites/default/files/geowebs/MCB/CBSbats_cat.htm) (accessed on 27  
1585 April 2018)

1586 Fenton, J.D., McKee, W.D., 1990. On calculating the lengths of water waves. *Coast. Eng.* 14, 499–513.  
1587 doi:10.1016/0378-3839(90)90032-R

1588 Flemming, B.W., 1980. Sand transport and bedform patterns on the continental shelf between Durban and  
1589 Port Elizabeth (Southeast african continental margin). *Sediment. Geol.* 26, 179–205.

doi:10.1016/0037-0738(80)90011-1

Gallagher, E.L., Elgar, S., Thornton, E.B., 1998. Megaripple migration in a natural surf zone. *Nature* 394, 165–168. doi:10.1038/28139

Glenn, S.M., Grant, W.D., 1987. A suspended sediment stratification correction for combined wave and current flows. *J. Geophys. Res.* 92, 8244–8264. doi:10.1029/JC092iC08p08244

Gomez, B., Naff, R.L., Hubbell, D.W., 1989. Temporal variations in bedload transport rates associated with the migration of bedforms. *Earth Surf. Process. Landforms* 14, 135–156. doi:10.1002/esp.3290140205

Grant, W.D., Madsen, O.S., 1979. Combined Wave and Current Interaction With a Rough Bottom. *J. Geophys. Res.* 84, 1797–1808

Grifoll, M., Navarro, J., Pallares, E., Ràfols, L., Espino, M., Palomares, A., 2016. Ocean–atmosphere–wave characterisation of a wind jet (Ebro shelf, NW Mediterranean Sea), In *Nonlinear Processes in Geophysics*. pp. 143–158. doi:10.5194/npg-23-143-2016

Guerrero, Q., Guillén, J., Durán, R., Urgeles, R., 2018. Contemporary genesis of sand ridges in a tideless erosional shoreface. *Mar. Geol.* 395, 219–233. doi:10.1016/j.margeo.2017.10.002

Guillén, J., Palanques, A., 1993. Longshore bar and trough systems in a microtidal, storm-wave dominated coast: The Ebro Delta (Northwestern Mediterranean). *Mar. Geol.* 115, 239–252. doi:10.1016/0025-3227(93)90053-X

Guillén, J., Soriano, S., Demestre, M., Falqués, A., Palanques, A., Puig, P., 2008. Alteration of bottom roughness by benthic organisms in a sandy coastal environment. *Cont. Shelf Res.* 28, 2382–2392. doi:10.1016/j.csr.2008.05.003

Jestin, H., Bassoullet, P., Le Hir, P., L’Yavanc, J., Degres, Y., 1998. Development of ALTUS, a high frequency acoustic submersible recording altimeter to accurately monitor bed elevation and quantify deposition or erosion of sediments. In: *OCEANS’98 Conference Proceedings (Vol. 1)*. pp. 189–194



- 1614 Jiménez, J.A., Sánchez-Arcilla, A., 1993. Medium-term coastal response at the Ebro delta, Spain. *Mar.*  
1615 *Geol.* 114, 105–118. doi:10.1016/0025-3227(93)90042-T
- 1616 King, C.A.M., Williams, W.W., 1949. The Formation and Movement of Sand Bars by Wave Action.  
1617 *Geogr. J.* 113, 70–85
- 1618 Kleinhans, M.G., 2005. Phase diagrams of bed states in steady, unsteady, oscillatory and mixed flows. In:  
1619 SANDPIT End-Book. pp. Q1–Q16
- 1620 Li, M.Z., Wright, L.D., Amos, C.L., 1996. Predicting ripple roughness and sand resuspension under  
1621 combined flows in a shoreface environment. *Mar. Geol.* 130, 139–161. doi:10.1016/0025-  
1622 3227(95)00132-8
- 1623 Li, M.Z., Amos, C.L., 1999. Sheet flow and large wave ripples under combined waves and currents: Field  
1624 observations, model predictions and effects on boundary layer dynamics. *Cont. Shelf Res.* 19, 637–  
1625 663. doi:10.1016/S0278-4343(98)00094-6
- 1626 Li, M.Z., Amos, C.L., 1998. Predicting ripple geometry and bed roughness under combined waves and  
1627 currents in a continental shelf environment. *Cont. Shelf Res.* 18, 941–970. doi:10.1016/S0278-  
1628 4343(98)00034-X
- 1629 Li, M.Z., King, E.L., 2007. Multibeam bathymetric investigations of the morphology of sand ridges and  
1630 associated bedforms and their relation to storm processes, Sable Island Bank, Scotian Shelf. *Mar.*  
1631 *Geol.* 243, 200–228. doi:10.1016/j.margeo.2007.05.004
- 1632 Maier, I., Hay, A.E., 2009. Occurrence and orientation of anorbital ripples in near-shore sands. *J.*  
1633 *Geophys. Res. Earth Surf.* 114, 1–18. doi:10.1029/2008JF001126
- 1634 Malarkey, J., Davies, A.G., 2012. A simple procedure for calculating the mean and maximum bed stress  
1635 under wave and current conditions for rough turbulent flow based on Soulsby and Clarke's (2005)  
1636 method. *Comput. Geosci.* 43, 101–107. doi:10.1016/j.cageo.2012.02.020
- 1637 Masselink, G., Austin, M.J., O'Hare, T.J., Russell, P.E., 2007. Geometry and dynamics of wave ripples in

- 1638 the nearshore zone of a coarse sandy beach. *J. Geophys. Res. Ocean.* 112, 1–19.  
1639 doi:10.1029/2006JC003839
- 1640 Naqshband, S., Ribberink, J.S., Hulscher, S.J.M.H., 2014. Sediment transport distribution along  
1641 developing sand dunes. *River Flow*
- 1642 Nelson, T.R., Voulgaris, G., 2014. Temporal and spatial evolution of wave-induced ripple geometry:  
1643 Regular versus irregular ripples. *J. Geophys. Res. Ocean.* 119, 664–688.  
1644 doi:10.1002/2013JC009020.Received
- 1645 Nelson, T.R., Voulgaris, G., 2015. A spectral model for estimating temporal and spatial evolution of  
1646 rippled seabeds. *Ocean Dynamics* 65, 155–171. doi 10.1007/s10236-014-0801-y
- 1647 Nelson, T.R., Voulgaris, G., Traykovski, P., 2013. Predicting wave-induced ripple equilibrium geometry.  
1648 *J. Geophys. Res. Ocean.* 118, 3202–3220. doi:10.1002/jgrc.20241
- 1649 Nielsen, P., 1981. Dynamics and Geometry of Wave-Generated Ripples. *J. Geophys. Res.* 86, 6467–6472
- 1650 Nielsen, P., 1992. Coastal bottom boundary layers and sediment transport. *Advanced Series on Ocean*  
1651 *Eng.* vol. 4. World Scientific, Singapore, pp. 324
- 1652 Reesink, A.J.H., Bridge, J.S., 2009. Influence of bedform superimposition and flow unsteadiness on the  
1653 formation of cross strata in dunes and unit bars - Part 2, further experiments. *Sediment. Geol.* 222,  
1654 274–300. doi:10.1016/j.sedgeo.2009.09.014
- 1655 Reesink, A.J.H., Bridge, J.S., 2007. Influence of superimposed bedforms and flow unsteadiness on  
1656 formation of cross strata in dunes and unit bars. *Sediment. Geol.* 202, 281–296.  
1657 doi:10.1016/j.sedgeo.2007.02.005
- 1658 Sánchez-Arcilla, A., González-Marco, D., Bolaños, R., 2008. A review of wave climate and prediction  
1659 along the Spanish Mediterranean coast. *Nat. Hazards Earth Syst. Sci.* 8, 1217–1228.  
1660 doi:10.5194/nhess-8-1217-2008
- 1661 Simarro, G., Guillén, J., Puig, P., Ribó, M., Lo Iacono, C., Palanques, A., Muñoz, A., Durán, R., Acosta,

1662 J., 2015. Sediment dynamics over sand ridges on a tideless mid-outer continental shelf. *Mar. Geol.*  
1663 361, 25–40. doi:10.1016/j.margeo.2014.12.005

1664 Soulsby, R.L. 1997. Dynamics of marine sands. A manual for practical applications. Thomas Telford,  
1665 London, ISBN 0-7277-2584-X

1666 Soulsby, R.L., 2006. Simplified calculation of wave orbital velocities. In: *Sand Transport in Oscillatory*  
1667 *Flow*. HR Wallingford, p. 12

1668 Soulsby, R.L., Clarke, S., 2005. Bed Shear-stresses Under Combined Waves and Currents on Smooth and  
1669 Rough Beds, Estuary Processes Research Project (Est Proc)/Defra project FD1905

1670 Soulsby, R.L., Whitehouse, R.J.S., 1997. Threshold of sediment motion in coastal environments. In:  
1671 *Proceedings of the Pacific Coasts and Ports'97 Conference*, Centre for Advanced Engineering,  
1672 Christchurch, NZ, pp.149–154

1673 Soulsby, R.L., Whitehouse, R.J.S., 2005. Prediction of Ripple Properties in Shelf Seas - Mark 1 Predictor  
1674 (Report TR 150)

1675 Soulsby, R.L., Whitehouse, R.J.S., Marten, K.V., 2012. Prediction of time-evolving sand ripples in shelf  
1676 seas. *Cont. Shelf Res.* 38, 47–62. doi:10.1016/j.csr.2012.02.016

1677 Sternberg, R., 2005. Sediment transport in the coastal ocean: a retrospective evaluation of the benthic  
1678 tripod and its impact, past, present and future. *Sci. Mar.* 69 (Suppl., 43–54.  
1679 doi:10.3989/scimar.2005.69s143

1680 Thorne, P.D., Davies, A.G., Bell, P.S., 2009. Observations and analysis of sediment diffusivity profiles  
1681 over sandy rippled beds under waves. *J. Geophys. Res.* 144

1682 Traykovski, P., 2007. Observations of wave orbital scale ripples and a nonequilibrium time-dependent  
1683 model. *J. Geophys. Res. Ocean.* 112. doi:10.1029/2006JC003811

1684 Traykovski, P., Hay, A.E., Irish, J.D., Lynch, J.F., 1999. Geometry, migration, and evolution of wave  
1685 orbital ripples at LEO-15. *J. Geophys. Res.* 104, 1505–1524. doi:10.1029/1998JC900026

1686 van Rijn, L.C., 2007a. Unified View of Sediment Transport by Currents and Waves. I: Initiation of  
 1687 Motion, Bed Roughness, and Bed-Load Transport. J. Hydraul. Eng. 133, 649–667. doi:10.1061/  
 1688 (ASCE)0733-9429(2007)133:7(776)

1689 van Rijn, L.C., 2007b. Simple General Formulae For Sand transport In Rivers, Esturies and Coastal  
 1690 Waters

1691 van Rijn, L.C., 2007c. Unified View of Sediment Transport by Currents and Waves. II: Suspended  
 1692 Tranport. J. Hydraul. Eng. 133, 668–689. doi:10.1061/(ASCE)0733-9429(2007)133:7(776)

1693 Venditti, J.G., Church, M., Bennett, S.J., 2005. Morphodynamics of small-scale superimposed sand  
 1694 waves over migrating dune bed forms. Water Resour. Res. 41, 1–14. doi:10.1029/2004WR003461

1695 Wiberg, P.L., Harris, C.K., 1994. Ripple geometry in wave-dominated environments. J. Geophys. Res.  
 1696 99, 775–789. doi:10.1029/93JC02726

1697 Wiberg, P.L., Nelson, J.M., 1992. Unidirectional flow over asymmetric and symmetric ripples. J.  
 1698 Geophys. Res. 97, 12745–12761. doi:10.1029/92JC01228

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1701 **Figures caption**

1702 Fig. 1.(a) Ebro Delta location. (b) Subaerial Ebro Delta shaded-relief and bathymetric contours offshore  
1703 with location of the sand ridge field in grey. Location of tripod, sediment sample and the Buda Island  
1704 meteorological station.

1705 Fig. 2. Image of the tripod structure during the deployment manoeuvres on the deck of the ship on 13  
1706 October 2013. Numbers indicate the position of the instruments used here: (1) video camera; (2)  
1707 currentmeter; and (3) altimeter.

1708 Fig. 3. Time series from October to December 2013 of (a) seabed configurations distinguishing the  
1709 morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross),  
1710 ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated  
1711 significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots)  
1712 at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability)  
1713 measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013

1714 shown in Detail from 23 October to 16 November of the same time series variables as those described in  
 1715 the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing  
 1716 the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples  
 1717 (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b)  
 1718 propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and  
 1719 direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic  
 1720 variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16  
 1721 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as  
 1722 those described in the caption of Time series from October to December 2013 of (a) seabed  
 1723 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
 1724 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1725 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1726 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1727 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1728 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1729 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1730 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1731 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1732 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1733 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1734 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1735 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1736 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1737 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1738 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1739 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1740 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1741 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from

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1745 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1746 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1747 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
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1752 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1753 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1754 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1755 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1756 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1757 series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple  
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1743 Fig. 4. Bottom sediment grain size distribution of the surficial sample (0-1 cm) at the tripod location on  
1744 the 13<sup>th</sup> of October of 2013.

1745 Fig. 5.Detail from 23 October to 16 November of the same time series variables as those described in the  
 1746 caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the  
 1747 morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross),  
 1748 ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated  
 1749 significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots)  
 1750 at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability)  
 1751 measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013  
 1752 shown in Detail from 23 October to 16 November of the same time series variables as those described in  
 1753 the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing  
 1754 the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples  
 1755 (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b)  
 1756 propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and  
 1757 direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic  
 1758 variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16  
 1759 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as  
 1760 those described in the caption of Time series from October to December 2013 of (a) seabed  
 1761 configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples  
 1762 (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1763 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1764 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1765 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1766 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1767 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1768 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1769 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1770 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1771 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1772 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from



1773 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1774 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1775 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1776 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1777 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1778 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1779 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1780 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1781 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1782 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1783 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1784 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1785 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1786 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
1787 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
1788 series variables as those described in the caption of Time series from October to December 2013 of (a)  
1789 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
1790 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
1791 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
1792 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
1793 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
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1775 Fig. 6.Example of the undulations observed in the instantaneous images from the video record on 1  
1776 November at 19 h.

1777 Fig. 7.(a) Sinuosity and (b) ripple crest direction box plots of the four periods when different ripples  
1778 morphologies were observed.

1779 Fig. 8.Example of 2D ripple formation observed in the instantaneous images (a) on 27 October at 23 h;  
1780 (b) benthic community contribution to ripple degradation on 28 October at 19 h; and (c) on 4 November  
1781 at 3 h.

1782 Fig. 9.Example of ripple formation under current-dominated conditions observed in the instantaneous  
1783 images on (a) 4 November at 19 h; (b) 4 November at 23 h; (c) 5 November at 3 h; (d) 5 November at 19  
1784 h; (e) 6 November at 3 h; and (f) 6 November at 19 h.

1785 Fig. 10.Example of 3D ripple formation under wave-current-dominated conditions observed in the  
1786 instantaneous images on (a) 29 October at 7 h; (b) 29 October at 15 h; (c) 29 October at 23 h; (d) 30  
1787 October at 3 h; (e) 31 October at 3 h; and (f) 31 October at 7 h.

1788 Fig. 11.Time series from October to December of (a) turbidity in normalized turbidity units (NTU)  
1789 measured at ~1 mab; (b) wave and current Shields parameter ( $\theta$ ) and the thresholds of initiation of  
1790 sediment motion ( $\theta_{crit}$ ), wash-out ( $\theta_{wash}$ ) and sheet flow ( $\theta_{sheet}$ ); (c) total sediment transport rate ( $Q_{total}$ ), suspended sediment  
1791 transport rate ( $Q_{susp}$ ) and bedload sediment transport rate ( $Q_{bed}$ ); (d) ripple wavelengths in cm from observations  
1792 (red dots) and obtained with the ripple predictor of Soulsby et al. (2012) (black dots); and (e) ripple  
1793 wavelength in cm from observations and obtained with the ripple predictor of Soulsby et al. (2012) (black  
1794 dots). Grey-shaded areas indicate the interval times when the Shields parameters (waves and/or currents)  
1795 were greater than the critical threshold, and coloured shaded areas indicate the periods of ripple

development detailed in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time series variables as those described in the caption of Time series from October to December 2013 of (a) seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c) current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time

1824 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1825 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1826 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1827 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1828 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1829 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1830 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1831 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1832 series variables as those described in the caption of Time series from October to December 2013 of (a)  
 1833 seabed configurations distinguishing the morphologies or states observed: flat bottom (circle), wave  
 1834 ripples (square), wave-current ripples (cross), ripple decay or degradation (inverse triangle), undulations  
 1835 (triangle) and no data (star); (b) propagated significant wave height in m (line) and direction (dots); (c)  
 1836 current speed in m/s (line) and direction (dots) at the tripod location at ~1 mab; (d) orbital velocity (); and  
 1837 (e) a (seabed topographic variability) measured at 20 cmab. The blue shaded area indicates the detail from  
 1838 23 October to 16 November 2013 shown in Detail from 23 October to 16 November of the same time  
 1839 series variables as those described in the caption of Fig. 3. The coloured shaded areas indicate the ripple  
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1825 Fig. 12.Detail from 23 October to 16 November of time series of (a) wave and current Shields parameter  
 1826 () and the thresholds of initiation of sediment motion (), wash-out () and sheet flow (); (b) total sediment  
 1827 transport rate ( $q_t$ ), suspended sediment transport rate ( $q_s$ ) and bedload sediment transport rate ( $q_b$ ); (c)  
 1828 ripple wavelengths in cm from observations (red dots) and obtained with the Soulsby et al (2012) ripple  
 1829 predictor (black dots); and (d) ripple height in cm from observations and obtained with the Soulsby et al

1830 (2012) ripple predictor (black dots). Grey-shaded areas indicate the interval times when the Shields  
1831 parameters (waves and/or currents) were greater than the critical Shields parameter.

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